THE UNIVERSE
IN SPACE AND TIME

THE UNIVERSE IN SPACE AND TIME

By

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THE UNIVERSE IN SPACE AND TIME

CHAPTER I

OUR EARTH

GREAT interest is shown in many circles in the problems with which the science of astronomy is occupied. This fact need not surprise us. Any person who reflects on the nature of things enquires into their "Why" and "How," their "Whence" and "Whither." He feels and understands that, before he can even try to find an answer to the first and most momentous questions of life, he must first endeavour to ascertain his own position in the whole system, in the Universe. Let us, therefore, set out on this great voyage of discovery.

Earth and World

We start out on our journey on earth, on *our* Earth, the stage on which man's life is acted. When we speak of our Earth we are inclined to think of an immense entirety, so vast as scarcely to be grasped even in one's thoughts. We frequently call the Earth "the World." We speak of a thing that has never "in the world" happened before, of a voyage "round the world." Without realizing it, we are inclined to consider the "Earth" and the "world" as identical. We shall have to learn to feel the tremendous difference between "Earth" and "world;" we shall have to understand and fully realize that the Earth, *our* Earth, is but a mere speck on the vastness of the World.

Shape and Dimensions of the Earth

First of all, we must try and get some idea of the shape and dimensions of our Earth.

We are all perfectly aware that the Earth is a sphere, i.e. more or less the shape of a tennis-ball. I say we *all* know that, and, indeed, that will no doubt apply to all readers of this book. Yet even nowadays there are very many people in the world from whom this primary, simple truth is completely concealed. These may be found in the interior of Africa—and, so far as that goes, even very much nearer home! There are many more who do, indeed, know that the Earth is "round," but to whom this fact has never yet been quite clear. We shall revert to this subject presently.

For centuries mankind was unaware of the true shape of the Earth. The primitive mind sees the Earth as a flat surface (apart from mountains and valleys) stretching out on all sides. This primitive person is only familiar with a small part of that flat surface, of the surface of the earth. In so far as he ever gives it a thought, he assumes that the surface, the land, extends endlessly in all directions. He cannot imagine it ending, for what would be beyond it if it did? Oh yes, he thinks, suddenly remembering, the land does end; beyond it comes the sea, the ocean, the endless ocean. Or else: somewhere the land stops; and there a bottomless abyss yawns—we have reached the "end" of the Earth. If we go one step further, we "fall off the Earth." The Earth then is a kind of disk, an enormous lump of earth, resting on—well, what? On this point man in olden times gave free rein to his fantasy. On an elephant, in its turn supported by a tortoise, and so on, in endless variety. Many insoluble difficulties presented themselves to these seekers. They saw the sun and also the moon and the stars rise in the East and set in the West. The next morning there was the sun again in the East, ready to start on its new day's journey. Where had the sun passed the night and how had it come back to the other side? Had it, as some held, actually plunged into the Ocean, passed through immeasurable depths and emerged again on the other side? The more the explanations the greater the enigma!

One must admit that the primitive mind of the untrained man was faced with a poser: he could not imagine the surface of the earth ending anywhere; there could not be a boundary, for if there were, what was beyond it? And it was just as hard for him to imagine infinity, real infinity, "never ending anywhere." And yet the solution, once you know it, is so simple!

A football is hanging in my room. Look, there is a fly walking about on it. Nowhere on the surface of the ball does it find a boundary. Indeed, there can be no limit, for what would there be on the other side of it? The surface of the ball is boundless; the fly can continue its walk in one and the same direction for the rest of its life. But the surface of the ball is not *infinite* by any means, we can in fact express it exactly in square inches.

This is indeed simple; you can even explain it to a child of six. But simple as it is, it gives one an insight into a truth of which mankind as a whole for centuries had no inkling, notably, that a surface can quite well be boundless, without being infinite. Let us hold on to this distinction between boundless and infinite; later on, when we come to the far more difficult problem of the infinity or non-infinity of the Universe, it may be of great use to us.

The Surface of the Earth is Unbounded, but not Infinite

As with the football, so it is with the Earth. The Earth is a sphere. Its surface is unbounded (although there are far too many boundaries on earth) but not infinite! Notwithstanding the difficulties of the problem, it is yet surprising that in the history of mankind the realization of the Earth's "roundness" took so long to penetrate into the mind of man generally. For there are phenomena, quite simple phenomena, in everyday life that could not possibly be explained if the Earth were flat. I refer to the phenomena connected with the existence of the *horizon.*

The Skyline

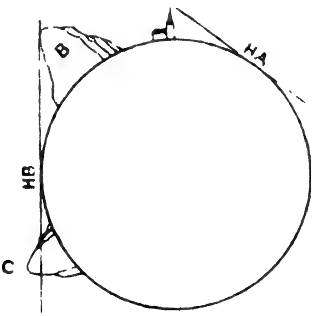
Beyond the skyline, which (as we shall see presently) is only a few miles away from us, our sight cannot penetrate. Is that due to the weakness of our eyes? Surely this cannot be the reason: we see the moon, the sun, the stars, which are many more miles away from us. But even the very best telescope cannot make us see the church steeple at a distance of some twenty or thirty miles. It remains hidden from our view "behind the horizon." There are other things that need explaining. We are standing on the sea-shore, on the beach. A big ship is in sight. We can see the whole ship, we see her bows cleaving the water. She travels away from us, leaves the coast and makes for the open sea. And then—we all know what happens next—after some time we can only see the upper parts of the ship; if we look at her through a telescope we see the funnel and the masts sticking up out of the water. Slowly the vessel disappears from our sight into, or rather, *behind* the waves. After a while only a wisp of smoke is to be seen above them!

Has the ship sunk? It is quite easy to convince ourselves of the contrary. We were standing on the beach, and now we climb the cliff. Slowly the steamer rises again from the waves. From the top we find that the ship has again become fully visible and we can follow her through our telescope until she again vanishes behind the sea.

How different all this would be if the surface of the Earth were flat! We should then see the ship getting smaller and smaller; the details would fade to the naked eye. But a good telescope would enable us to see her again with perfect clarity. And in bright clear weather a very powerful telescope, such as is used by astronomers, would enable us to follow the vessel to the Dutch coast. This coast itself would then also be visible on a clear day.

But that is not how we see things. There is a horizon, not very far away from us, which moves further away the

higher we climb. If we were on the open sea we should easily be able to ascertain another fact, namely, that whichever way we look the horizon is invariably the same distance away from us: the horizon is a circle of which we are the centre. All these phenomena can only be explained if the surface of the Earth is curved, and equally curved in all directions. Look at Fig. 1. It leaves little to explain. There *must* be a horizon, for rays of light travel in a straight line; or, more simply, because one cannot "see round the



DISTANCE OF THE HORIZON

The proportion of all heights and distances is greatly exaggerated. Standing at the top of the steeple A, the horizon is seen in HA. Standing at the top of the mountain B, the horizon is seen in HB; from this point the summit of the mountain C is also visible.

corner." The drawing also makes it clear why it is that the higher you stand the further you can see. We said one cannot see round the corner. That statement is not quite true. One *can* see round a corner if a mirror is put in the right position to enable one to do so. If it were possible to hang a gigantic mirror "above the horizon," one would be able to see beyond it. On rare occasions, in the British Isles very rarely, nature itself provides such a mirror. If hot and cold strata (layers) of air meet in a certain way, rays of light can sometimes be deflected from their rectilinear path on the boundary of these strata; they are broken and reach our eye from "round a corner." This is what we

call a "mirage," a *fata morgana.* We are then given a glimpse of what is beyond the horizon.

How far away from us is the horizon?

It is not at all difficult to calculate the distance to the *horizon in a given case. All we have to know is how high* we are standing, or, to be more accurate, *how high* our *eye* is. We cannot explain the reasoning of this calculation here, but the calculation itself is very simple indeed. The height of an adult is upwards of 5½ feet. Let us assume that his eye is exactly 5½ feet from the ground.

Suppose him to be standing at the sea-shore, close to the water, at a height of 0 feet; the position of his eye will be 5½ feet above sea-level. We now multiply 5½ feet by 3 and divide it by 2. This gives a little more than 8. We now find what number must be multiplied by itself to get 8. $2 \times 2 = 4$. That is too little. $3 \times 3 = 9$. That is too much. The number wanted is therefore nearly 3, and the horizon is about 3 *miles* away from us. If we climb a cliff that is 100 feet high, our eye is 105½ feet above sea-level. $\frac{3}{2} \times 105\frac{1}{2} = 158$. What figure multiplied by itself produces 158? $12 \times 12 = 144$. That is too little. $13 \times 13 = 169$. That is too much. The number must therefore lie between 12 and 13. The horizon is now about 12½ miles away from us.

If we ascend a steeple 320 feet high, we find in the same way that the horizon is about 22 miles away from us. It must not be forgotten that we can then still see the upper part of a church steeple some miles further away, or some other high point. But the *surface* of the Earth touches the sky, to our eye, at a distance of 22 miles. On a high peak of the Alps, 13,000 feet, we can see for about 143 miles. From an aeroplane 33,000 feet high we can get a view of places as far distant as 284 miles. And from the highest altitude ever reached in a stratosphere balloon (about 15½ miles) we should be able to see for about 355 miles. But even then our sight would only range over a small portion

of the crust of the Earth, i.e. only a piece with a diameter of 710 miles.

Briefly, for those who are familiar with the most elementary principles of algebra, we may say that if we are standing at an altitude of *h* feet (position of the *eye*) the *horizon is at a distance of* $\sqrt[2]{\tfrac{3}{2}h}$ *miles.*

The fact that the horizon, whichever way we look, is an equal distance away from us, wherever we are, proves that the surface of the Earth has approximately the same curvature in all directions. The Earth is, however, not quite spherical, but is slightly flattened at the Poles. But the difference between the diameter in one direction and that in the other is only very small. The distance from Pole to Pole is 7,895 miles, and the distance from one point on the Equator to another exactly opposite is 7,922 miles, the difference being 27 miles, or about one part in three hundred.

The phenomena occurring in connection with the horizon are proofs, as simple as they are obvious, of the spherical shape of the Earth. It is a matter for astonishment that these facts did not lead mankind sooner to realize the spherical shape of the Earth. Yet it is not altogether a matter for astonishment, for one must admit that the most usual phenomena, to which one has been accustomed from childhood, are the least conspicuous; and because they are not conspicuous, the untrained human mind requires no explanation of them. Someone once asked a native belonging to a very backward tribe what his people thought about the rising and setting of the sun, about the alternation of day and night. It transpired that they had never thought about it at all. All these "ordinary" facts are accepted without their cause being enquired into; but if, on the other hand, some unusual phenomenon occurs, such as an eclipse of the sun, the simple mind tries to find an explanation. It seems, therefore, that people do not feel the need of explaining the disappearance of a ship as it travels away from us. If it were suddenly to return to their view,

through a mirage, they would try to find out how this came about.

This will have to be borne in mind, not only now, but again and again as we continue our voyage through the world.

There are some other reasons why an unschooled man cannot conceive the idea of the Earth being round, and why, when once he has been told so, he even refuses to believe it. Even among the readers of this book there will be some who do not mind accepting the fact that the Earth is a sphere, if only because so many respectable and clever people tell them so, but who, on the other hand, deep in their hearts have first to overcome an inner conviction to the contrary. And why? Certain objections may be made, which some people find it impossible to explain. Let us put them as briefly and simply as possible. If the Earth is round we must have "antipodes," i.e. people that live on the opposite side of the Earth.

Our Antipodes

If we walk "on top" of the Earth, they "hang" on to it head "downwards." How is that possible? Common sense protests against this. And it is even stranger to think that we are ourselves antipodes to our antipodes, and they have the same difficulty to get over with regard to us as we have with respect to them! Why do we not fall off the Earth? Do we, also, walk head downwards and feet upwards?

Is not the Ocean Water-level?

There is another insurmountable difficulty to our simple reader. He might think, if he had enough knowledge about physics to be a dangerous thing, that water is "water-level," and that a curved surface of water is an impossibility. But if the Earth is a sphere, then surely the surface of the Earth, and therefore of the oceans too, is as curved as curved can be. How is that possible?

These arguments against the roundness of the Earth are so strong to an untrained mind that it is no wonder that it took a long time before the idea of the Earth being spherical was generally accepted. Mankind in general would probably have had even more difficulty in believing in the roundness of the Earth, if a proof had not been *forced* upon them when the first voyage round the "world" was accomplished.

The First Voyage Round the Earth

Not very long after the discovery of America by Columbus (1492), Magellan (Magalhaes), a Portuguese sailor, left Seville with three ships (1519). He sailed westwards and reached America. Travelling down the east coast of South America, he discovered the straits that to this day bear his name. Through these straits he entered the waters of the Pacific Ocean. Continually sailing westwards, Magellan reached the Philippine Islands, where he was killed in a fight against the natives (1521). Two of his ships were lost. But the third, under Captain del Cano, sailed further to the west, through the Indian Ocean, doubled the Cape of Good Hope, and returned to Seville by way of the Atlantic Ocean (1522). The first voyage round the Earth was accomplished in three years. Continually sailing, mostly westwards, del Cano had returned to his starting-point. This proved even to the most doubtful-minded that the Earth could not but be round. We shall now try to remove the difficulties mentioned above.

"Above" and "Below" are Relative Terms

The solution to the problem of the antipodes is essentially quite simple. To understand this look at Fig. 2. The ship between the ice-bergs at the North Pole looks as if it is sailing properly, the right way up. Here there are no difficulties. But the poor penguins at the South Pole appear to be standing upside down. How is that? Why do not they drop off the Earth?

To find the answer, we need only ask ourselves what we really mean when we speak of "above" and "below."

Everybody has at some time or other heard of gravitation. In obedience to the laws of gravity a stone dropped from my hand falls to the Earth. If it were not stopped in any way, it would continue its fall to the centre of the Earth.

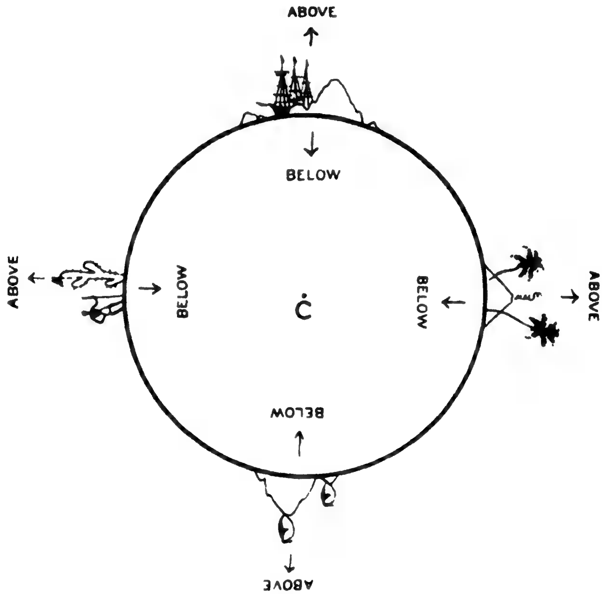
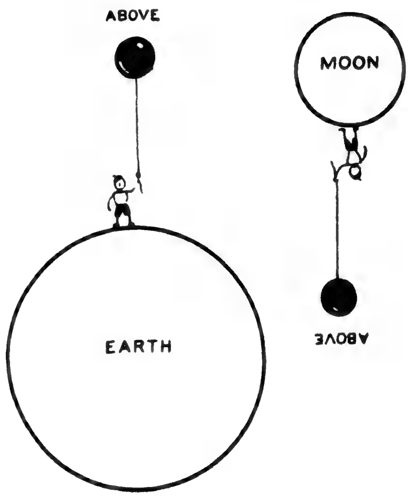


Fig. 2
"Above" and "below" are relative ideas.

We say that the stone falls "downwards," meaning that it moves in the direction of the centre of the Earth. In other words: the term "downwards" has on Earth no other meaning than *towards the centre of the Earth;* the expression "upwards" means exactly the same as *away from the centre of the Earth.* In the world-space there is not one certain direction that can be indicated by the term "upwards," or one other that can definitely be called "downwards." There is no absolute, no definite "above" and "below." The penguins at the South Pole are standing the right way up;

the smoke coming out of the volcano ascends upwards; the spear that the Zulu is holding points upwards (Fig. 2). There is therefore nothing to be surprised at. Every person on the surface of the Earth, wherever he is, occupies the same position with respect to the ideas "above" and "below."

There is no absolute "above" and "below" in the world-space any more than there is any definite direction to the left or to the right on the Earth. When I look at the moon



Above on Earth and Above on the Moon.

high up in the sky, I look "upwards." If at the same moment an inhabitant of the moon (let us assume for the sake of argument that there *are* people on the moon) is watching the Earth, he will not be looking "down" at the Earth, but also "up" at it. For he obeys the laws of gravity of the moon; the stone that he drops from his hand falls "downwards," that is, in the direction of the centre of the moon, and he sees the Earth high up "above" him in the sky. The inhabitants of the Earth and of the moon are looking at one another and both are looking "upwards." The "upwards" of one is exactly the opposite of the

"upwards" of the other, and they are both right (*see* Fig. 3). This is one of the first of many ideas that we always regarded as absolute that proves to be only relative. Learning to look upon things as relative which have hitherto been regarded as absolute is often the only way to get a better insight into their nature.

So the problem of the antipodes is no longer a problem. And now what about the surface of the ocean that is not water-level? The solution to this problem is just as simple. Water-level or *horizontal* is the direction that forms a right-angle to the vertical direction, to the imaginary line from the surface down to the centre of the Earth. Just as there is no absolute "upwards" or "downwards," neither is there any absolute "horizontal" level. The direction in the world-space that is horizontal at a certain spot on the Earth is not horizontal at some other point. And for the very reason that the water of the oceans is horizontal everywhere, the surface of the ocean must curve with the surface of the Earth.

The horizontal line of a building is not a straight line in the world-space; it is part of the circumference of a circle whose centre coincides with the centre of the Earth. In the same way, the perpendicular at one end of a building is not exactly parallel to the perpendicular at the other end; of course the difference is very slight: the lines intersect in the centre of the Earth.

The usual points arguing against the round Earth are therefore of no significance; on the contrary, more clearly than before we now realize that we could not possibly imagine the Earth to be a flat body. So the Earth is indeed a sphere, and we shall now have a closer look at the dimensions of that sphere.

The Earth is a Sphere

The diameter of the Earth is something under 8,000 miles, the radius (half the diameter) is therefore about 4,000 miles and the circumference about 25,000 miles. Hence

there are no places further away from each other in a straight line on the surface of the Earth than 12,500 miles. A few more figures: the area of the surface of the Earth is 196,500,000 square miles; the cubic content more than 250,000,000,000 cubic miles; weight of the Earth 6,000 trillion tons.[1]

It is difficult to get a good mental picture of these dimensions. We all know what a mile is, but we can

THE EARTH WEIGHS

6,000,000,000,000,000,000,000 TONS

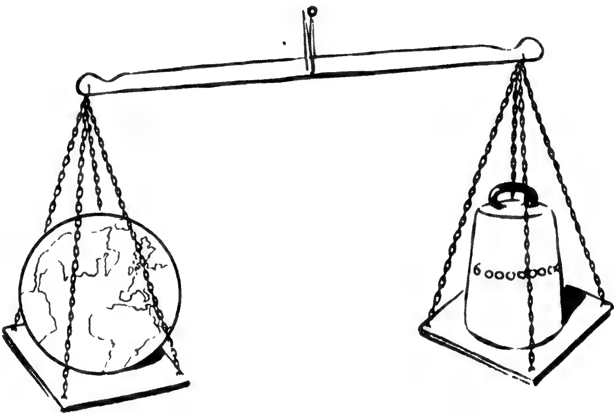


Fig. 4

scarcely realize the four thousand miles separating us from the centre of the Earth. To visualize this it is a great help to imagine a model of the Earth and then to think out the size, in comparison with it, of objects that are more or less familiar to us. Our model, then, is a globe with a diameter of some five feet, reaching to about our chins. The highest peaks of the Alps that the reader has ever seen, perhaps only on the pictures, or perhaps actually scaled by himself

[1] A million = 1,000,000; a milliard = a thousand times a million = 1,000,000,000; a billion = a million times a million = 1,000,000,000,000; a trillion = a million times a billion = 1,000,000,000,000,000,000; a quadrillion = a million times a trillion = 1,000,000,000,000,000,000,000,000.

with great effort, are on this globe, in the correct proportions, a little over half a millimetre high (that is, about a fiftieth part of an inch)! The globe must be turned very truly indeed to be able to make such a minute elevation perceptible at all, and this represents our mighty Alps! Mount Everest, the highest peak in the world, almost 30,000 feet high, protrudes just over one millimetre from our model. The deepest parts of the Ocean, about 33,000 feet deep, will show a dent a little more than a millimetre deep. So the irregularities in the surface of the Earth, the highest mountains and the deepest seas, are, in proportion, only very slight.

The shape of the Earth is almost exactly round, with very little irregularities. Here and there the Earth is covered with an extremely thin film of water—the "unfathomable" oceans. A football that has been taken out of a puddle is, in proportion, wetter than the Earth. The greatest depth to which anybody has ever descended into the interior of the Earth in a mine (nearly 4,000 feet) can scarcely be indicated on our model. Just a scratch with a pin is sufficient. The deepest hole ever drilled is about twice as deep. We inhabitants of the Earth are indeed limited to an extremely thin layer of our Earth. Neither have we ever succeeded in ascending high up away from it. Professor Piccard managed to rise two millimetres from the surface in his stratosphere balloon! This is quite negligible. Man cannot get away from the surface of the Earth, his dwelling-place. He remains, even in a balloon at its highest altitude, relatively close to the surface of the Earth, two millimetres away from it on our model. On a small-sized globe, as seen on writing-desks, this height can scarcely be indicated, even a particle of dust is almost too high.

Round the Earth there is a layer of air, called the atmosphere. People who have not studied the matter sometimes think that the air reaches infinitely far from our Earth. This is by no means the case: the layer of air round the Earth is quite thin; we can best demonstrate

this by the aid of our model. But now we are faced by a particular difficulty: it is not such a simple matter to indicate the boundary of our atmosphere, for it has no fixed boundary. The further distant we get from the Earth, the thinner the air gets. At a height of 7,000 feet some people begin to feel mountain-sick, the rarefied air makes them feel unwell for a time. Beyond 16,000 feet conditions of living become very difficult; beyond 30,000 feet life becomes an impossibility. Aviators who wish to mount as high as that in a balloon or aeroplane must take air with them, or better still, oxygen, or else they must make the ascent in an air-tight compartment. At an altitude of 60 miles the air gets rarefied to a degree of vacuum which can scarcely be obtained with the best air-pump. And then comes the gradual transition to the vacuum of the world-space. If we take the boundary of our atmosphere to be 60 miles away from the surface of the Earth, this is about half an inch from our model. And the actual air, in which man can breathe, in which all meteorological phenomena happen, the air that yields our clouds, wind, gales, rain, hail and snow, is only a millimetre thick on our model. We repeat: every single phenomenon of the weather takes place in that thin layer of air immediately encircling the "skin" of the Earth, and nearly every phase of it occurs in the lower half of that thin layer.

Is it not indeed true that most people usually imagine all this to be quite different? Do not some clouds seem almost as distant as the moon sailing "through" them? And yet the moon is 100,000 times as far away from us as they. (In relation to our model we should have to place the moon at a distance of about 160 feet.)

Life on Earth is indeed confined to a thin layer. Towards the inside we can only penetrate a five-thousandth part of the distance to the centre. Down there, 4,000 feet deep, it is almost unbearably hot: the temperature rises nearly two degrees Fahrenheit per 100 feet that we move from the crust inwards. Leaving the Earth we have two enemies

to reckon with, lack of air and cold. Even in the height of summer in our country the frost line is seldom more than 13,000 feet away from us, and never more than 20,000 feet. At an altitude of 30,000 feet temperatures prevail, even in summer, that are never found on the surface here in this country. There it is 50° or 60° F. below freezing-point.

Having got some idea of the shape and dimensions of our Earth, we shall now deal with its rotation.

The Rotation of the Earth

The earth rotates—as we all know. It rotates round its axis in twenty-four hours, alternately exposing each of its sides to the sun. As a result of this the sun appears to rise and to set, and the alternation of day and night is created which is of such tremendous importance to all life on Earth. The Earth revolves round an (imaginary) axis running straight from Pole to Pole, the Poles being points on the Earth where the axis reaches the surface. The easiest way to understand this is by having a good look at an ordinary globe. You will then at once see how the Earth rotates: a spot on the Equator, half-way between the North Pole and the South, travels the farthest distance in one rotation, namely the entire circumference of the whole Earth, which is almost 25,000 miles; the closer a point is to either of the Poles, the smaller will be the circle, while the Poles themselves are stationary. A man who stands exactly at the North or South Pole rotates once in 24 hours on his own axis.

At the Equator, in Central Africa for instance, the motion will be the fastest. Every point on the surface of the Earth at the Equator travels 25,000 miles in twenty-four hours, that is, 18 miles a minute and over 500 yards per second. Being further away from the Equator the rate will be less in Great Britain; but it will still be more than 300 yards a second. Over 600 m.p.h. is still a respectable rate at which to move. There is not an aeroplane in the world that can

keep up with this space; the very swiftest seaplanes do not go beyond 450 m.p.h.

We in our country, as a consequence of the Earth's rotation, fly round at a rate of more than 600 m.p.h. And we never even notice it! Is it surprising that there are still so many people that can scarcely believe in this movement? The difficulty that always confronts them is the fact that we never feel ourselves moving at this lightning speed.

But here again the explanation is not hard to understand. If we move along at a constant speed, without shocks or vibration, we are unable to perceive that motion, *unless there is something else that does not move with us.* We need go no further than the motion in an ordinary train to convince ourselves of this fact. If we travel in a train at night, with the blinds down, we are aware whether we are moving or not, but we only derive this knowledge from certain facts that have really nothing to do with the actual motion. We feel shocks and vibration, we hear creakings and rumblings. Besides this, our bodies are inclined to move backwards or forwards when the train accelerates or slows down suddenly. But if the movement of the train were perfectly even, and if the rails were absolutely smooth, we should not notice we were moving at all. This is conclusively proved from the following fact. When the blinds are down, we do not know in which direction we are travelling. As long as we do not look out of the windows we have no means of telling in what direction the train is going. Every movement inside the compartment is the same as if the train were not moving. If it did not bump and vibrate, we should be able to play a game of billiards. The movements of the balls would not in any way be influenced by the rate at which we were travelling.

All this is even more striking in an aeroplane. In favourable atmospheric conditions an aeroplane glides along almost without bumping. If you sit in the cabin without looking down to the Earth, you are scarcely conscious of any movement at all, at whatever rate you are actually

travelling. If you are flying very high, and look down at the Earth, you can hardly realize how fast you are travelling, for the Earth seems to be creeping past you down there. You seem to be moving at a snail's pace. This sensation is most perfectly felt in an ordinary old-fashioned balloon. If there is a slight, even wind, there is no means (except by means of wireless direction finding) for the balloonist to know whether he is moving or not, other than by looking at the Earth below. If this is impossible, owing to vapours enveloping him, he cannot judge whether he is in motion, or if so, the rate at which he is travelling. This is not merely theory; it has repeatedly occurred in actual life. A cloud-bound balloonist cannot tell whether he is moving, because there is no object anywhere from which he can conclude his movement by comparison.

Rest and Motion are Relative Terms

Now that we have got so far, we can go a step further and ask what we really mean when we say that some person or thing is moving. This question looks strange: When do I move and when am I standing still? This seems quite simple and easy to decide. Yet it is not as simple as it looks. We can make this clear by some examples. I am travelling in a corridor train. I stand at the end of the corridor. The train has just been stopping at a station, and now begins to move again. Slowly the train draws out from the station along the platform, while I start to walk down the corridor in the opposite direction, at exactly the same rate as the train is moving. Am I really moving? With respect to the train most decidedly, but with respect to the platform, to the whole Earth, I am perfectly stationary. Must I say that I am really standing still? It would seem to be so. But then I remember that the Earth, as we shall explain later on, revolves very rapidly round the sun, and therefore moves with respect to the sun. Even although, walking along the corridor of the train, I am stationary

with regard to the Earth, yet it will be clear that I am moving with respect to the sun. Hence I am moving through world space. But can I be quite sure about that? We have been told that the sun, too, travels through the world space, with respect to the stars. If now this movement should at a certain moment prove to be at exactly the same rate and in exactly the opposite direction to that of the Earth round the sun, I must conclude that I am, after all, standing still in the world space. But what about the stars? Do they stand still or do they move as compared with something else? If they do, what about that other something? Does it in its turn move or not?

The reader will feel what a tangle we are in. It is impossible to give a satisfactory answer to the question as to whether we are moving or not. We can never get beyond saying that we move or are stationary as the case may be, with respect to some other object. And now we can take a definite step forwards. There is no point in raising the question as to whether I am moving or not in an absolute sense; *it is a meaningless question.* Both a negative and an affirmative answer can be given to it, whatever object it concerns, in any circumstance. The only question which *has* sense and which can be answered is whether a thing is moving or stationary with respect to some other object.

Let us find a simple example. Try to imagine the whole world space as being empty, absolutely empty, but for one single object. In all that vacant space, extending unbounded in every direction, there is only one object: a stone, or a star, or whatever you like to fancy. And now consider, is there any sense, has it any significance, to say that this object travels through space? Remember, the space we imagine is empty, it does not even contain air. If you think about it at your ease, you will realize that it is quite meaningless to say that this object moves. If we say that the stone or whatever we have chosen as our example is stationary, it is right. No one can prove the contrary.

If we say that it travels at a rate of five or ten or a thousand or a million miles a minute, that is right too. Here again no one can prove the contrary. But the most correct way of putting it is to say that there can be no question of rest or motion, because these terms are meaningless unless they apply to objects that can be compared with some other object. Absolute rest or absolute motion cannot exist. As soon as a second body, a second stone, appears in our imagined universe, we can speak of motion or rest of one of the stones with respect to the other. We perceive that one of the stones moves with regard to the other, that the distance from stone A to stone B increases 100 yards a minute. But if, again, we ask whether the reason for this is because stone A is at rest and B is moving away from it, or because B is at rest and A is moving in the opposite direction, or (a third possibility) because A and B are moving in opposite directions while the sum of the rates at which they are travelling is 100 yards a minute, *then again these questions are meaningless and have no significance.* For, with regard to what would A and B be at rest? It was assumed that they were moving with respect to each other. And there is no third object to compare them with. Thus we must come to the remarkable conclusion that rest and motion are not *absolute* terms either, but that we can only speak of rest and motion with respect to something else, so of *relative* rest and motion.

This brings us to the principles of the celebrated Relativity Theory. As we all know, this theory was evolved some twenty-five years ago by Professor Albert Einstein.[1] The full purport of this theory is so difficult to understand that it is quite impossible to give a popular explanation of it. Such an explanation would not be complete, because to grasp this theory fully it is necessary to be well acquainted with higher mathematics. Consequently we shall not venture

[1] Of course this theory did not drop from the skies suddenly. It must rather be looked upon as the conclusion of a long series of developments. This development was helped along by the great Greek mathematician Archimedes, by Galileo and Newton, by the eminent Dutch scholar Lorentz, and finally completed by Einstein.

to try and explain the relativity theory, but consider that we need not omit mentioning these principles, which, with a little effort, anybody can understand. So we see that not only *absolute "above" and absolute "below" do not exist, but neither do absolute motion or absolute rest.*

The Rotation of the Earth

Let us now go back to the rotation of the Earth. At the latitude upon which England is situated, we travel at a rate of more than 600 miles per hour relative to the axis of the Earth. And we know now how it is that we are unaware of this fact in everyday life, that we cannot notice it because the movement is perfectly regular, without bumping or jerking, and because all the objects round us, even the thin layer of air "clinging to" our Earth, move at exactly the same rate with us.

However, the other heavenly bodies, the sun, moon, planets and stars, do not rotate with us. So, obviously, we must be able to see that we move with respect to those bodies. And, indeed, we can. We see the sun, moon and stars moving across the sky every day. The Earth moves from West to East round its own axis; that is why we see the whole celestial sphere revolving from East to West in the same period as the Earth turns on its axis.

But is it not possible that the Earth does not rotate, but that in reality the sun, moon and stars, the whole vault of heaven, travel round the Earth in twenty-four hours? As we know, this was at one time believed. It was then thought that the Earth was stationary in the midst of the Universe, and that all the other heavenly bodies moved round the Earth. As science developed this theory proved to be untenable. When the scientists became acquainted with the distances and the sizes of the various heavenly bodies, as we shall see further on in this book, the original conception could not be maintained any longer. To give but one example (and not the most striking by far): whoever

could possibly believe that the sun really rises and sets and travels all round the Earth in twenty-four hours, now that it has been proved that the sun is more than a million times as large as the Earth and over 90,000,000 miles distant from us? For this would not only mean that a giant's course was determined by that of a dwarf, but that, moreover, the giant (that is the sun) travelled a distance of more than 600,000,000 miles every day, and think of the distance which would have to be travelled by the stars which are millions of times further away. There is, therefore, only one possibility left. The Earth rotates round its axis in twenty-four hours. And we shall see presently that, *if only we are observant enough*, there are plenty of phenomena on Earth by which we can directly prove the rotation of the Earth.

How Time is Regulated

The Earth makes a complete turn from West to East in twenty-four hours. As a consequence, the sun rises in the East in the morning and sets in the West at night. Day and night alternate. It is many thousands of years ago that mankind divided the day into twenty-four hours, the hours into sixty minutes and the minutes again into sixty seconds. When the sun reaches the centre of its apparent path between the two horizons and hence (in the Northern hemisphere) stands in the South, it is midday, or twelve o'clock. But it will be quite clear to the reader that if I move ever so little to the East or the West, the moment of midday and also that of sunrise and sunset cannot remain the same. The Earth turns from West to East; the further to the East a place is situated, the sooner it will be lit by the sun's rays, hence the sooner the sun will rise. You will understand that if I move a distance of $\frac{1}{24}$ of the circumference of the Earth to the East it means that I see the sun rise an hour earlier. And even in Great Britain a move to the East or the West makes a considerable difference. In the extreme East of this country the sun rises seven minutes

sooner than it does in Greenwich and also sets seven minutes earlier. At Land's End the difference from Greenwich will be about twenty-two minutes the other way. It is only when we move exactly to the North or exactly to the South, that there is no change at all in the solar time, in the exact moment of midday (in summer or winter it does make a difference in the rising and setting of the sun if we move North or South; but this is due to quite different causes, as we shall see later). There are, therefore, lines running from North to South that have the same solar time. These are called "meridians." Thus we can draw a line running through the Royal Observatory in Greenwich, exactly from North to South, and call that the meridian of Greenwich. All along this line there is the same solar time. But any other place to the East or West of this line goes by some other time. But you will realize that it would be most unpractical if every town or village had its own particular time. That is why, by international agreement, the Earth has been divided into twenty-four strips, in each of which the time differs one hour. Thus, in the middle of Europe, in the strip running through Scandinavia, Germany, Switzerland, Austria and Italy, they have Central European time; in Britain, Belgium, France, Spain and Portugal, Western European time (Greenwich time); in the East of Europe, Eastern European time. In England (not considering Summer Time, which we shall deal with later) the time is an hour earlier than in Germany, in Germany an hour earlier than in Russia, and so on.

Thus the whole Earth is divided into twenty-four zones. Everywhere in the world the minutes past, or to, the hour are the same, only the whole hour differs. For instance, it is a quarter to seven in England at the moment that it is a quarter to eight in Germany. There are a few exceptions to this arrangement, and only one of importance. This is made by Holland. At the moment (1936) Holland has not yet joined the other countries in their method of regulating the time. Holland goes by its own time, that

of the steeple of the West Church in Amsterdam, which differs 19 minutes 32 seconds (and a fraction) from Western European time.

Uniformity of time in a wide zone does not only offer advantages. On the eastern boundary of a zone (say, at the French Riviera) the sun rises half an hour to three-quarters of an hour "too early," which, except in winter, has little advantage; but on the other hand, the sun sets as much "too early" all the year round, which must always be felt as a drawback, as, to mention but one thing, it involves using artificial light sooner. In this respect it is much better to be situated on the western boundary of the zone.

The introduction of what has become known as "Summer Time" rather alters all this—thus England, Belgium and France have Western European time in winter and in summer Central European time.

A Day Lasts Forty-eight Hours

The different countries of the Earth, therefore, as far as they are situated to the West or East of each other, have a widely different hour, and sometimes a different date. If it is eleven o'clock at night on, say, May 9 in the East of America, then in the whole of Europe and Asia May 10 has dawned. It begins to be May 10 in the East of Asia, and every hour May 10 makes a hop from the East to the West, chasing May 9 before it to the West. So we see that even the hour and the date are not absolute, they are relative ideas. And the same naturally applies to a week, month or a year. On New Year's Eve the New Year approaches us hour by hour; once it has reached us it continues its march inevitably to the West. A telegram dispatched from here on January 1 at one o'clock in the morning will reach America in the evening of December 31 of the preceding year. In America one can hear through the wireless music played "next year" in Europe.

Seeing that a certain day, say the first of January, proceeds from East to West over the Earth in stages of

an hour, that day must be born somewhere in the East and die somewhere in the West. Every day lasts forty-eight hours! It begins its life in the Western half of a certain zone of time (we shall explain this presently); every hour it occupies a fresh zone, until at the end of twenty-three hours it has included the whole world in its grasp, except for the eastern half of the zone of time in which it started its career. At the end of twenty-four hours it takes this last strip in its stride, but must at the same time yield up the very first strip (the Western half of the first zone) to its successor, January 2. And the latter in its turn pushes poor tired old January 1 off the Earth hour by hour. Forty-seven hours after its birth January 1 only rules over the Eastern half of the first zone. At the end of forty-eight hours it dies—at the very moment that the third of January is born in the Western half of the first zone. Hence the actual end of January 1 and the true commencement of January 3 coincide!

See here a few simple facts that usually escape our notice. How long does a certain day last? Forty-eight hours! How much time is there between the first and third of January? None at all!

The Date Line

Somewhere in the East the new day starts. But this "East" may be anywhere, for the position of East depends entirely on the point from which we determine it. Somewhere or other there must be a boundary, a line to the West of which the new day is considered to have begun, while to the East of this line the previous day still holds sway. This line must be somewhere on Earth, it is impossible that it should not exist. The following example will make this clear to us. Imagine that I have a tremendously swift aeroplane, that will take me round the Earth in a few seconds. I fly eastwards and in the countries under me it is an hour later every time I pass over a fresh zone. At the end of a few seconds I have flown round

the Earth and land at the point I started out from. But I passed over twenty-four zones of time successively, and in every zone it was an hour later, so I land more than twenty-four hours after my departure! And if I were to fly westwards, it would be an hour earlier every time and I should arrive almost twenty-four hours before my departure!

Both feats are equally impossible, and there *must* therefore be a date line, which puts both these absurdities right. This boundary might be made anywhere on the Earth

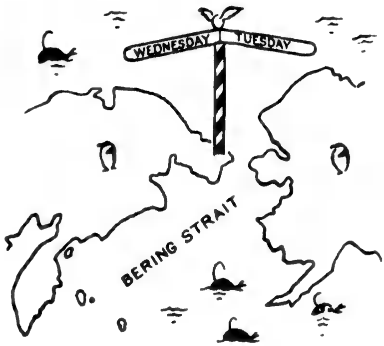


Fig. 5
THE DATE LINE.

providing it ran from North to South. It is, however, most practical to place it in such a position that it does not run through any country, for this would give rise to all sorts of complications. This matter has been arranged by international agreement. The date line runs lengthwise through the twelfth zone East of Greenwich (which is also the twelfth zone West of Greenwich) and therefore follows the 180th meridian.[1] Here and there, for practical reasons, it deviates slightly to the East or West. Its exact course is as follows: East of the eastern point of Siberia through the Bering Strait, East of Japan, the Philippines, New Guinea

[1] This also has the advantage that the time nowhere on earth differs more than 12 hours from Greenwich meantime.

and New Zealand.[1] There are only a few small groups of islands in the Pacific Ocean that are to the East and West of the line and close together. This does not matter much in practice. In the zone of time through which the date line passes, the same hour is adhered to, but a different date.

When sailing from Japan to America the date line is soon reached. And it must not be thought that this happens without your noticing anything. In the most drastic form, too. For you go to bed on, say, Tuesday, August 5, you pass your usual peaceful night, and wake up the next morning on—Tuesday, August 5! In the ship's log-book this is recorded as Tuesday, August 5, I, and Tuesday, August 5, II. If the date line is traversed in the night between a Sunday and a Monday, the next day is not a second Sunday, but is called Monday I and the day after that Monday II. The Saturday *is* repeated, however, and that can make things rather difficult for orthodox Jewish people.

If, on the other hand, you are travelling from America to Japan, a day is not gained, but lost. You go to bed on Monday night, sleep the usual number of hours and wake up on Wednesday. If it happens to be your birthday on the Tuesday, you have to skip it that year. The Sunday is never missed out, but the Sabbath is!

If Phineas Fogg, in Jules Verne's celebrated book *Round the World in Eighty Days*, had remembered the existence of the date line, he would never have made his famous mistake. He thought he had arrived a day too late; but then he would have known that he was exactly in time.[2]

The fact that there are different zones of time is the

[1] Until 1845 the Philippine Islands belonged to the Eastern time group; but from December 30, 1844, it became the next day, January 1, 1845. Until 1867 Alaska belonged to Russia, hence to the Western group; it was then transferred to the United States and to the Eastern group. Samoa became Western in 1892.

[2] An inventor of the stuff that inventors of perpetual motion are made of, thought he could find a means of rejuvenating people by the aid of the date line. The idea was to fly continually from West to East somewhere near the Pole, and hence to traverse the date line again and again every few minutes. In this way one was to become a day younger every few minutes! What was the mistake he made?

The reader will also understand that the zones of time are broadest at the Equator and narrower the nearer we get to either of the Poles. If you sail to the East or West in the Arctic Ocean a zone is traversed in a comparatively short time, so that watches repeatedly have to be adjusted. At the very Poles all zones meet; when the clock strikes twelve there, it is also one, two, three o'clock, and so on. And when we remember that the zones of time are purely artificial, arranged by man for his own convenience, and that in reality every line running from North to South has its own time, as we explained above, a clock exactly at the North Pole always shows the right time, whatever hour it points to. Even a clock that does not go indicates the exact time there. That is one of the advantages of a house built exactly at the North (or South) Pole. There is another advantage to a dwelling at the North Pole, all the windows have a southern aspect! And there is always a south wind!

After this little excursion to the North Pole we must now return to the rotation of the Earth. We have seen that the alternation of day and night, or sunrise and sunset, may be regarded as the first proof of the rotation of the Earth round its axis. But there are many more. We shall consider some of them more closely.

PROOFS OF THE ROTATION OF THE EARTH

Foucault's Pendulum Test

One of the ways of proving the Earth's rotation is by the aid of Foucault's pendulum test, made in the Panthéon

the revolving summer-houses that people sometimes have in the country, in order to be able to turn the windows to face the sun or not, as they wish. If, now, we hang a pendulum inside one of these at the very centre of the roof, so that it can swing freely in any direction (for instance by suspending it from a gimbal ring) we can make the following experiment. We swivel the house round so as to have the motionless pendulum, the opening of the door of the hut, and a certain thick tree in the garden in one straight line. We then set the pendulum vibrating in the direction of the middle of the door opening, and hence of the thick tree. Then we carefully start to turn the hut, very evenly without jerking it. We turn it the quarter of a circle. If we have carried out the conditions of the experiment accurately, the pendulum will continue to swing in the direction of the tree, and will therefore be at right-angles to the middle of the opening of the door. If I had stayed inside the hut and someone else had turned it without my noticing it, I should suddenly have seen, no doubt to my great astonishment, that the plane in which the pendulum was swinging was no longer in the direction of the door, but had, in a short time, shifted no less than 90°. I should not for a moment imagine that some change had taken place in a law of nature; I should understand that the swing of the pendulum could not possibly change its direction and I should therefore conclude that, without my noticing it, the hut had been turned 90°. And if I were to look outside I should be able to convince myself of this fact; the plane of motion has remained unchanged; the pendulum is still swinging in the direction of the thick tree; only the hut has turned a quarter of a circle round the pendulum.

In the same way this experiment can be applied to prove

the Earth's rotation. In theory (alas, not in practice!), this is simplest at either of the Poles. Let us take the South Pole, as this is on a large continent. We build a large dome-shaped building at the point of the Pole, and inside, a hundred yards from the ground at the highest point of the dome, we fix our pendulum as prescribed. The cord of the pendulum is more than ninety yards long and there is an enormous, heavy weight, of some hundreds of pounds, at the end of it. So it must all be made very firmly and strongly. At the bottom of the weight there is a fine point, no bigger than a needle. Under our pendulum there is a table, which bends up a little towards the edges. The table is covered with fine sand. All our apparatus is placed in such a way that the pendulum, when once it starts to swing, just touches the grains of sand with its fine point, and so traces a slight furrow in the sand.

We make our experiment during the Polar night. It is dark outside, and, standing inside the building near the pendulum, I can see through the middle of the opening of the door a bright star shining just above the horizon. Now I set the pendulum swinging; some special device is required for this purpose, the pendulum is so heavy. The swing of the pendulum is directed exactly towards the middle of the opening of the door, and hence precisely in the direction of the bright star I saw just now. The first trace is made in the sand; it is a fine sharp line. Before the pendulum has swung more than a few times we see that a change has taken place; the fresh line does not exactly coincide with the first. The pendulum swings on for a long time—let us assume that after six hours have passed it is still swinging. And what do we see now? During those six hours the plane of motion has turned further and further, until at the end of that time the latest trace is at right-angles to the first. The pendulum no longer swings in the direction of the middle of the door. The line of motion is now at right-angles to what it first was, and is directed towards a point in the dome, where, not far from the ground there is a

window. But what do I see now? Through the window I am looking at a bright star. Can I be right? Indeed, it is the same one I was looking at before. The swing of the pendulum has remained unchanged in the direction of the star!

What has happened is exactly the same as what was described in the summer-house. The thick tree is the star. The plane of motion of the pendulum has remained the same, but evidently the large dome-shaped building at the South Pole has turned 90°! Of course it has! It must have turned, owing to the Earth's rotation through exactly 90° in six hours.

We have imagined this experiment at the Pole, because there the results would be the easiest to interpret. At that point the dome, just as the summer-house, turns exactly round the pendulum suspended from a stationary point. If we made the experiment at the Equator, it would be a complete failure. That would be seen most clearly if at that point we were to swing the pendulum from West to East, that is in the same direction as the Earth rotates. There is no reason why there should then be any change in the direction that the pendulum swings, with respect to the dome. And, if we think it over carefully, we shall all understand that, whichever way we vibrate the pendulum, the result will invariably be the same at the Equator. As soon as we move away from the Equator, however, and again get nearer to either of the Poles, the experiment will be a success; and the nearer we approach the Pole the better we shall be able to see the change in the direction of the pendulum.

It was on this principle that Foucault made his famous experiment in the Panthéon in Paris, in 1851. He had made about the same arrangements as we have described above for our experiment at the South Pole. The result was amazing; after not more than a few vibrations of the pendulum the direction of the trace in the sand began to veer. In after years the experiment was often repeated, invariably

with the utmost success. For the advantage of those who wish to make this experiment too, it must be observed that everything must be prepared with the greatest care. They must make quite sure that no single factor can possibly influence the swing of the pendulum, and anyhow, the best thing to do is to make use of a long and very heavy pendulum.

The Effect of Centrifugal Force

Considering that the Earth, particularly at the Equator, rotates round its axis with comparative velocity, it is to be expected that in that part we may be able to detect some effect of centrifugal force. Now we know that at the Equator, say in Central Africa, people are not slung off the Earth, so the action of this force cannot be so terrible there after all. And yet, if it is true that the Earth turns on its axis, it cannot be altogether absent. So we must find a way of showing that it does exist, as indeed we can.

People in Central Africa are not whirled into the air. But that would only be possible if the effect of centrifugal

So we must prepare things differently if we wish our experiment to succeed. We must use some other kind of weighing machine, that works with a spring or some other device, instead of a counter-weight. Now, if we can find a balance accurate enough, we shall find that the bag of sugar that weighed two pounds in England has lost in weight in Africa. The difference, however, is slight. Our spring balances can quite well be used in Africa, unless it concerns something that has to be weighed with very great precision. If the Earth turned on its axis a little faster than it does, our athletes would go to the Equator to improve their records, most certainly for high-jumping.

The fact, therefore, that a weight at the Pole is heavier than it is here and is less in Africa, taken together with the known figure of the Earth, is one of the proofs that the Earth rotates. For the sake of completeness we must not forget to add here that this effect is heightened (by about

half) by the flattening of the Earth at the Poles. Therefore the differences in weight that we spoke of above are in reality 50 per cent. *higher.* At either of the Poles we are a little closer to the centre of the Earth than we are at the Equator, and for this reason, too, the effect of gravitation is a little stronger at the Poles. However, this flattening is also due to centrifugal force; when the Earth was still in a liquid state this force caused the Earth to bulge at the Equator and to be flattened at the Poles.

Finally, seeing that the effect of centrifugal force increases much more rapidly than the velocity of the Earth's rotation, this, even if it were only eighteen times what it is at present, would make it impossible to live in the tropics near the Equator; people really *would* be slung into the air. The Earth would then be a kind of "wheel of fun," at least in the tropics.

and the same applies to our attic and our cellar. That is why, up in the attic, the effect of centrifugal force is a little stronger and weight a little less (as we remarked just now), although the difference is so minute that it could only be shown by the aid of very delicate and exact instruments (here, too, the effect is increased by being further away from the centre of the Earth). There is quite an easy way, however, of demonstrating the fact that the roof of a very high building rotates more rapidly than its base, or that the top of a mine-shaft, or well, moves faster than the bottom. Suppose that we are standing at the mouth of a mine-shaft 500 feet deep. At a distance of about a yard from the edge, from the end of a stick I carefully lower a plumb-line. Down at the bottom of the mine-shaft there is somebody who determines exactly where my plumb-line touches the ground. This must be done with the utmost precision. The string of the plumb-line must be perfectly taut; no wind or other disturbing factors may influence it in the slightest. In this way it is possible accurately to determine the point on the ground that is vertically below the end of my stick. This point is carefully marked. I then take a ball of lead and hold it exactly at the point from where I dropped the plumb-line. I let go of the ball of lead and it drops down freely. There must be no pressure sideways whatever. It is by no means easy to eliminate this and it is advisable to think of some device by which to do so. The ball drops and, in our country, it will land at the bottom, 500 feet below, about an inch to the *East* of the point marked.

Who can tell me why? Before starting out on its downward journey the ball was exactly perpendicular to the point marked at the bottom of the shaft. But, for the reason which we stated above, it moved to the *East* more rapidly than this point. We took every possible precaution to prevent the ball from getting any sideways pressure. But there was one kind of pressure that we were powerless to cope with, and that was the greater eastward velocity. The result is the same as if I were to

have given the ball a slight push eastwards (supposing that there were no axial rotation) just hard enough to give it the same velocity as it has now in excess of the other point below owing to axial rotation. Anybody can make this experiment, even though they have not a mine to drop the ball into. Of course the less the height from which the object is dropped the less will be the deviation at the bottom, and particular care must be taken to avoid any disturbing influences, especially currents of air.

So our ball does not drop perpendicular to the Earth. And it is clear that nothing can fall quite perpendicular. Even a stone dropped from my hand to the ground does not fall perpendicular, though the deviation is minute. But even fractions of millimetres can be interesting sometimes.

The Clock Loses in Africa

We now come to the fourth proof, which is connected with the second. We all, at one time or another, have seen a pendulum clock. Whether this clock goes accurately or not depends on the length of the pendulum. That is why the material of which the pendulum is made must come up to very high standards; the length may not alter at all. If the pendulum stretches in heat or contracts in cold, the exact working of the clock is disturbed. For this reason good pendulum clocks have what is called a compensation pendulum, which automatically neutralizes the effect of heat or cold. You need not be an expert scientist to be able to understand that the swinging of the pendulum has something to do with gravitation, that the oscillation will become quicker if the force of gravitation is stronger. The same pendulum will, in otherwise identical conditions, vibrate more quickly at the Pole than here, and quicker in this country than at the Equator. Thus a pendulum a metre long will make 86,242 vibrations per 24 hours (*in vacuo*) at the Pole, at the Equator only 86,017 and in this country about 86,145. If you wish to

make the pendulum vibrate with the same velocity at the Equator as here, you will have to shorten it slightly. If the pendulum is a metre long it will have to be shortened about three millimetres, which is about $\frac{3}{25}$ of an inch. If this is not done, the vibration will be considerably too slow at the Equator and your clock will lose time.

Therefore, a pendulum clock that goes correctly in this country will be no good in Africa. This difference will be enough to cause inconvenience. The clock loses time, chiefly as a result of the Earth's rotation.

This was experienced by a seventeenth-century French astronomer when he went to Cayenne, which is not far from the Equator, for some astronomical studies. He was not aware of the fact that his journey would make any difference to the vibration of his pendulum. Part of his equipment was a fine pendulum clock made by the most celebrated watchmaker in Paris. Who shall describe his amazement and indignation when he found that his costly clock was no good in America and lost time badly! He was obliged to shorten the pendulum himself and then the instrument worked perfectly. But when, after some years, he returned to Paris, the clock again gave trouble, though now it gained time. The pendulum had to be lengthened again and then it dawned upon the astronomer that it was not the fault of the watchmaker but chiefly of the Earth's rotation. (About a third of this effect is due to the flattening of the Earth at the Poles.)

Ebb and Flow

Several other direct proofs may be offered. We here refer to phenomena that play a particularly important part in man's existence. There are, in the first place, the ebb and flow of the tides. The tidal wave is caused by the attraction of the moon and the sun. Owing to its being nearer the Earth than the sun is, the moon has the stronger effect.[1] So, to begin with, we may deal with the matter as

[1] *See* note on p. 161.

if it were only the moon that caused the tides. The water of the ocean on the side of the Earth facing the moon is drawn towards the moon, so that under the moon it is a few yards higher (*see* Fig. 6). At the same time, on the opposite

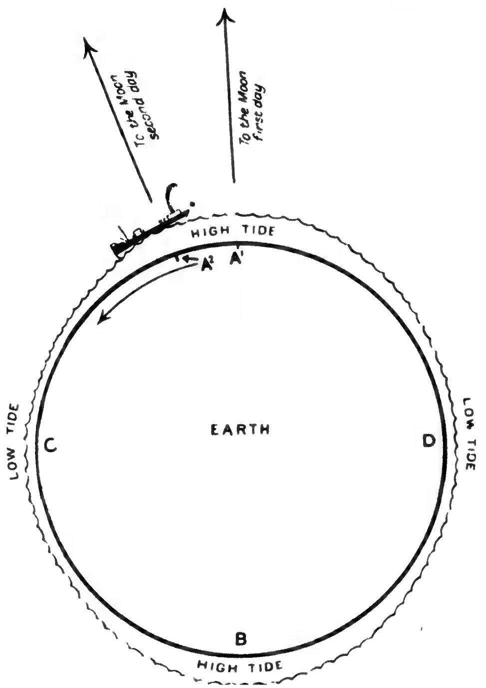


Fig. 6

SKETCH SHOWING THE EBB AND FLOW OF THE TIDES

The Earth turns in the direction of the arrow "away under" the tidal wave. The tidal wave remains "opposite" the moon. The moon takes about a month to revolve round the Earth in the same direction as the Earth's rotation. Point A^1 which has high tide at a given time of one day, will have to turn further the next, to A^2 (on an average about 50 minutes) before it has full high tide again.

side of the Earth, at B, a second high tide is formed. The cause of this second high tide is rather harder to see. But you will understand it if you bear in mind that the water at that point is furthest away from the moon and is hence attracted *less* than the rest of the water. Therefore, with respect to the other water, it drops away, so to speak, from

the moon. The result of this is the same as on the side facing the moon; at the "back" of the Earth it is also high tide. At the "sides" (C and D, Fig. 6) it is low tide, however. If, now, the Earth did not rotate, high tide would occur as follows. The high tide under the moon (to keep to this high tide for the moment) would move with the moon's movement round the Earth. But we know, and this will be dealt with in detail later, that the moon travels round the Earth in about a month's time. (The word month is derived from the word Moon.) Seeing that the moon travels from West to East, high tide would also move round the Earth from West to East in a month's time. And the opposite high tide too. It is not difficult to see that ebb and flow of the tides would last about a week every time. But this is where the Earth's rotation interferes. The Earth turns from West to East under the high tide. Hence, the tidal wave travels from East to West with respect to the Earth. This is also the case with the opposite tidal wave. If, now, *only* the Earth's rotation had anything to do with the matter the same point of the Earth ought to pass under the same tidal wave after 24 hours. As there are two tidal waves, high tide would be repeated every 12 hours. And that is, more or less, how things are. But the same high tide reaches the same point (on an average) almost an hour later. For the moon travels further on its voyage round the Earth. Look again at Fig. 6. When the point of the Earth indicated as A^1, which is exactly "under the moon," arrives in the same position after 24 hours, that is after one complete rotation, the moon is no longer straight "overhead." The latter has travelled on in the same direction. So our point has to move on further, to A^2, to catch up with the moon, before it can have full high tide. In view of the time the moon takes to travel round the Earth, the distance from A^1 to A^2 will be about a thirtieth of the circumference of the Earth, and therefore our point will require about an hour to reach A^2.

For various reasons, all this is in reality much more

complicated. In the first place, the sun also plays a part in the ebb and flow of the tides, as we already observed before. In this respect the sun and moon may work in the same direction, but they can also work counter to one another. At full moon and new moon they affect the tides in the same way; in the first and the last quarter they work counter to one another. The relation of the lunar tide to the solar tide is, on an average, 11 to 5.[1] So if they come together the tide will be about $11 + 5 = 16$ units (spring tide). If the effect of the moon and the sun run counter to each other the height of the tide will be $11 - 5 = 6$ units. Hence the relation of the height of high tide in the former case is to the latter as 16 is to 6, or 8 to 3. As a matter of detail it is not until a day after full moon or new moon that the co-operation between the sun and the moon reaches its maximum effect, and likewise the counter action of the sun is most effective the day after the first or last quarter.

Secondly, the distance of the moon has some influence on the height of the tide. We shall see presently (page 90) that the distance from the moon to the Earth fluctuates from 225,000 miles to 250,000 miles. When the moon is nearest the Earth (perigee) its "tide-raising force" will be about 20 per cent. greater than when it is farthest away (apogee). We can, therefore, expect the very highest flood tides when perigee occurs at the time of a new or a full moon. The change in the distance of the Earth to the sun also exerts some influence, but much less.

Thirdly, as a rule the height of the high tide under the moon is not equal to the high tide on the other side of the Earth. The cause of this is that as a rule the moon is not in the plane coinciding with the Equator of the Earth. On this account the tide-raising force of the moon is exerted on a slant as regards the plane of rotation of the Earth. It is only when the moon is in the plane of the Equator (which occurs twice a month) that both high tides are equal. So

[1] *See* note on page 161.

you see how many influences are at work upon the height of high tide. And we have only mentioned the most important.

It is only in very large expanses of water, in the oceans, that high tides of any significance can occur. Inland seas scarcely undergo this change, if at all (e.g. the Caspian Sea), not even when they open into the ocean (like the Mediterranean Sea and the Baltic). A tidal stream penetrates into the Mediterranean through the Straits of Gibraltar, but the basin of this sea is too large to permit of its being much influenced by it.

Finally, the coastal line of the oceans is a factor of importance in the progress of the tides. In funnel-shaped inlets the flood-water is sometimes forced up to a great height. This is the case along the English and French coasts in the English Channel. The tidal stream invades the North Sea through the Straits of Dover. At the same time a second tidal wave enters the North Sea round Scotland.

So you will understand that the simple explanation we have given above only applies to the fundamental principles; in reality all kinds of additional factors must be taken into account. But all the same, we must not lose sight of this basic principle. Then we shall realize how very different these phenomena would be if there were no rotation, for then it would only be high tide twice a month instead of twice a day.

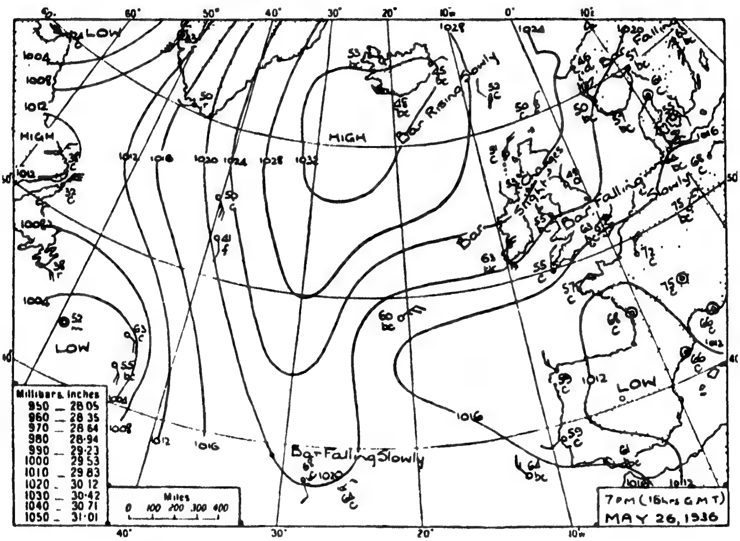
A last observation on this subject: the tidal wave, under which—in a certain sense—the Earth revolves, must to some extent counteract the Earth's rotation; this must retard rotation, so the day becomes longer. But do not be too quick in drawing your conclusions—the day does become longer, but by no more than a minute fraction of a second in a century. It will be tens of thousands of years before this becomes of practical importance. But in the long run, the *very* long run, it will make a difference. For the future of mankind is not measured by centuries, but by millions,

and thousands of millions of years. We shall say more about this later on.

Wind and Weather

The weather we have, too, is greatly affected by axial rotation. For the direction of the wind would be quite different without it. We all know that the direction of the wind is, in our country, determined by the distribution of atmospheric pressure round about us. We shall not deal with the causes of the distribution of this atmospheric pressure. However, if the distribution of pressure over Europe is known, the direction of the wind can at once be concluded. If, for instance, pressure to the North of us is higher than it is here, so that the barometer is higher there than here, or (which comes to about the same thing) lower to the South of us than in our country, then the wind is East, or, more exactly, East-North-East. If the barometer is highest to our West, then there will be a North wind (N.N.W.); to our East, a South wind (S.S.E.); to our South, a West wind (W.S.W.). It would be impossible to understand this if it were not for axial rotation. To give but one example: if pressure is high in the North and low here, we consider it to be a matter of course that the current of air travels from the high to the low pressure. Just consider: if I hold a book over my desk and then lower it, the air under that book comes under higher pressure than the surrounding air, and the air will be displaced from under the book in all directions. So if there is what is known as an anti-cyclone (high-pressure area) North of us, surrounded on all sides by lower pressure, air will flow away in all directions from that centre. This would mean that to the West of that centre there would be an East wind, to the East a West wind, to the North a South wind and to the South of the anti-cyclone a North wind. So, high pressure to the North of us would result in a North wind here. All this is quite simple and straightforward. But the reality is different; if there really is high pressure in the North we do not get a

North wind, but an East, at least an East-North-East wind. This is on account of axial rotation. Owing to this the direction of the wind is shifted almost 90° in the direction in which the hands of a clock move. (Buys-Ballot's law.[1]) That is, on the Northern hemisphere. (*See* the weather chart below.) As is the case with so many other phenomena, on the Southern hemisphere things are just the



By courtesy of *The Times*

other way round. There, the direction of the wind shifts in the opposite direction, not with the hand of the clock: a North wind becomes West (W.N.W.).

Now, how can we explain the influence of axial rotation on the direction of the wind, or, to put it differently, on the air-currents? This is by no means simple. It is extremely difficult to make this plain in a way that is easily understood by everybody. Let us first point out that there is some connection between this and the phenomenon we

[1] This law, which governs the direction of the winds, was first accurately formulated by the Dutchman Buys-Ballot.

observed in Foucault's pendulum test. The swing of the pendulum "desires" to remain in the same plane; this also applies to the direction of the air-current; this also tries to maintain its original direction and on the surface of the Earth this causes an *apparent* change in the direction because the Earth revolves away, as it were, under the air-current. This will scarcely make the matter clear to our readers, we fear, so here is a second explanation which is certainly not complete but has the advantage of being easy to follow:

We return to our North wind, which, owing to axial rotation, becomes Easterly. This means that air from the North is blown towards us. This air comes from a region where the rate of rotation is considerably lower than it is in this country. The Earth revolves to the East. Therefore the air coming to us from the North travels to the East more slowly than our air does. What impression will that give us? Imagine us travelling eastwards very rapidly in an aeroplane and catching up with another aeroplane flying eastwards at a less rapid rate. *We* fly past that aeroplane from West to East, but it makes the impression on us as if the other 'plane is moving past us from East to West. If for some reason or other the air round that other 'plane moves from West to East at the same rate as the aeroplane is travelling, that air will, with respect to our faster machine, move from East to West. So that the air will to us seem to come from the East. This is exactly what happens with the air that travels towards us from the North with a less rapid Eastern movement than our own air. With respect to *us* it moves in a westerly direction and therefore comes from the East. For a current of air from the South exactly the opposite applies. This comes from regions that rotate with greater velocity eastwards. Hence, this air continues to blow eastwards with respect to us too, and therefore comes from the West. And now it will also be obvious why the state of affairs on the Southern hemisphere is exactly the opposite. For on the Southern hemisphere a point

further to the North rotates with greater velocity; a point further to the South there travels more slowly to the East.

So we see that axial rotation greatly affects atmospheric conditions. In our latitude it alters the direction of the winds by almost 90°. It need hardly be said that this greatly influences our climate.

This also serves to explain the trade winds in the tropics. A current approaching the Equator from the North becomes the North-East trade wind (coming from regions of lower axial rotation); a current approaching the Equator from the South also comes from regions of lower axial rotation and becomes the South-East trade wind.

Sea Currents

In the direction of the currents of the oceans the influence of axial rotation may also be perceived. Many of these currents, as a matter of fact, owe their existence to the prevailing winds; and thus, though indirectly, axial rotation again plays its part. But obviously there must be some direct influence on the flow of the water. In principle the same forces are at work again. But owing to various circumstances, such as the contour of the coasts, its effects are sometimes more difficult to trace.

Putting it briefly we may say that we have seen that, if only we are observant enough, the Earth's rotation can be directly proved from numbers of phenomena of varying degrees of importance in the life of mankind. And that is not all. There are many extremely important phenomena that are due to axial rotation *together with other causes.* We shall say more about this later on. But we need no longer be in any doubt about this matter. The Earth rotates round its axis in 24 hours, or—to be more exact—in 23 hours 56 minutes and 4 seconds.

"What is this?" the reader will ask, "isn't it twenty-four hours exactly? Surely the day caused by axial rotation

lasts exactly twenty-four hours! What about the difference of almost four minutes?"

Solar Day and Sidereal Day

That is what we are now going to explain, and we must repeat here what has been observed time and again: the matter will prove to be quite simple. The earth's rotation does indeed take exactly 23 hours 56 minutes 4 seconds. Therefore, if we take accurate note of the moment at which a star, in its apparent daily revolution round the earth, passes an imaginary line in the sky, such as the North and South line directly overhead, or celestial meridian, we shall see that this is repeated the next evening exactly 23 hours 56 minutes 4 seconds later. And this goes on and on; night after night the star passes that line four minutes earlier. The apparent movement of the star and of the entire vault of heaven is, we all know, in reality caused by the Earth's rotation; this rotation, therefore, appears to occupy no more than 23 hours 56 minutes 4 seconds and consequently this space of time has been termed the *sidereal day.* (*Sidera* is Latin for stars.)

Night after night the stars "gain" four minutes, and all these tiny bits of time after a fortnight have accumulated to a full hour. To see the firmament exactly as it was a fortnight before, we must look up into the sky one hour earlier. After one month the difference is two hours, after one year twenty-four hours, when obviously the difference is righted. Only, it is clear that after a common year (not a leap year) the vault of heaven has not completed 365, but 366 revolutions, 366 sidereal days have elapsed, as against 365 solar days; or, in other words, the Earth has made 366 revolutions, but only 365 ordinary, that is solar, days have been completed.

Now for the explanation of all this. We all know that the Earth not only spins round on its axis but that, at the same time, in one year it makes one complete revolution round the sun. We will revert to this at length, but may

here assume this fact to be known to all our readers. Thus, the Earth, while spinning round on its axis, travels forward *in its orbit round the sun.* Fig. 7 will at once make this *clear.*

If point A_1 *on the Earth's surface (left), which sees the sun due South, has made one complete revolution it has arrived in* A_2, *because the Earth has in that time also moved*

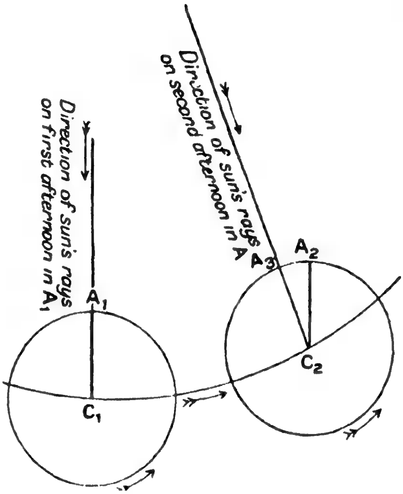


Fig. 7

Difference between Solar Day and Sidereal Day

After one complete rotation of 23 hours 56 minutes 4 seconds point A_1 *has arrived in* A_2. *It then requires another 3 minutes 56 seconds turning to* A_3 *for the sun to be seen in the South again.*

somewhat to the right. (This displacement has for clearness's sake been exaggerated in our drawing.) Now point A_1 has completed its revolution in exactly 23 hours 56 minutes 4 seconds; the directions C_1A_1 and C_2A_2 may be taken as identical in infinite space, so that upon completion of this movement a star (stars, as compared with the sun, are at infinite distances from us) will appear in exactly the same direction. But its position in relation to the sun has changed owing to the Earth's progress on its orbit round the sun: A_2 has to rotate a little further to see the sun again

due South. This will take point A_2 3 minutes 56 seconds, which clearly accounts for the difference between a solar day and a sidereal day.

This is all very interesting, the reader will probably say, but is it of any use in everyday life? We shall presently see that he is wrong in doubting this. To this end we must first finish our story. What is still left to be told is that the Earth does not travel round the sun at a uniform rate, but that in winter it goes slightly faster than in summer. Why this is so we shall see later.

And now it will be clear that when the Earth (*see* again Fig. 7) travels a greater distance in 24 hours, and consequently reaches a position further to the right, point A_2 will have to rotate just a little longer to see the sun due South! The 3 minutes 56 seconds will then be insufficient. The solar day will be more than 24 hours, although the greater difference will not exceed half a minute. If on December 25 the sun is in the South at exactly 12 o'clock, this will not yet be so on December 26. And now what has this to do with everyday life? We have all experienced that after the shortest day (December 21) the days begin to draw out rapidly in the evening; very soon the sun sets later, but in the morning things do not proceed so smoothly; as yet the sun does not, or if at all hardly, rise earlier. The following times of sunrise and sunset (for latitude 52° N.) will make this point quite clear:

SUN

	RISES	SETS
December 21	8.6 a.m.	3.50 p.m.
December 26	8.8 ,,	3.53 ,,
December 31	8.8 ,,	3.58 ,,
January 5	8.8 ,,	4.2 ,,
January 10	8.6 ,,	4.10 ,,
January 15	8.2 ,,	4.18 ,,

Note the great difference! Whereas on January 15 almost half an hour has been gained in the evening, there is a

gain of only four minutes in the morning—a difference of not less than 24 minutes.

The Equation of Time

Many people will have wondered at some time of their lives what may be the cause of this remarkable phenomenon. The solution is now within easy reach. We have seen that the Earth travels faster at this time of the year; the true solar day, about Christmas and New Year, lasts 24 hours and about half a minute. On December 21 the sun is seen in the South at 11.58, and on Christmas day at 12 o'clock sharp; on January 1 at 12.4, on January 15 at 12.10. The middle of the day, that is noon by the *true* solar time, is therefore in this period of the year continually shifted towards the evening of our "mean" solar day. Between this true noon, that is the hour at which the sun reaches the meridian, and sunset, there is the same lapse of time as between sunrise and true noon. True noon is at 11.58 on December 21, and at 12.10 on January 15, a difference of not less than 12 minutes. It is clear that if the day had not itself become at all longer, the sun, owing to this phenomenon which is called equation of time, would rise 12 minutes *later* and also set 12 minutes *later*. Hence 12 minutes' loss in the morning and a corresponding gain in the evening. The day, however, has become 32 minutes longer, of which 16 minutes go to the evening and 16 to the morning, so that on January 15 the sun, by our watches, which mark mean solar time, must rise $16 - 12 = 4$ minutes earlier than on December 21, and set $16 + 12 = 28$ minutes later. We can see in the above list that this squares with the facts.

That true noon in this period comes after mean noon with increasing differences, in other words, that the sun passes the meridian later every day, is easy to verify. On Christmas day at 12 o'clock Greenwich mean time (the time marked by our watches) the sun reaches the meridian. (Don't forget that this holds good only for the meridian of Greenwich; East of this line this point of time falls earlier,

West of it later). One can then, at exactly 12 o'clock, draw a line running exactly from North to South along the shadow of a perpendicular pole or tree in the garden or on the window-sill along the shadow of one of the window-bars. Now, if you possess a reliable watch or clock you will be able to notice after a few days—provided the weather is kind to you—that your line does not coincide with the shadow until a few minutes past twelve. Continue to watch your line for a couple of days and you will see the difference in time increase. (The experiment can also successfully be made in places not on the meridian of Greenwich; only your line will then not run exactly from North to South.)

Since, with a view to the exigencies of everyday life, it would be very inconvenient to have true solar time, people decided—not very much more than a century ago—to adopt mean solar time for their clocks. Sun-dials, however, unless provided with some ingenious device, still indicate true solar time. It will be clear that, even on the meridian of Greenwich, they will be fast or slow in certain periods of the year (irrespective, of course, of our modern summer-time). Mean and true solar time only coincide on four days in every year. We have already seen that about New Year the true solar day is longer than the mean one, and it stands to reason that the reverse must happen at other times of the year. There are two periods (one short and the other long) when a true solar day is shorter, and also two (one about equally short and the other about equally long) when a solar day is longer than the mean solar day of 24 hours. The complicated nature of this phenomenon is attributable to one factor other than the accelerated or retarded course of the Earth round the sun; but for the sake of simplicity we have so far only mentioned *that* cause. The second factor operating here is a little more difficult to grasp. It is the "inclination" of the Earth's axis, a point to which will be given proper attention later on. As a result of it the Earth's rotation about its axis and its revolution round the sun are not performed in the same plane. Con-

sequently, the outcome of these movements in relation to one another is subject to slight variations in the course of the year.

The following table shows true noon, that is the moment at which the sun passes over the meridian of Greenwich, on different dates:

Jan.	1	12.04	May	1	11.57	Sept.	15	11.55
Jan.	15	12.10	May	15	11.55	Oct.	1	11.49
Feb.	1	12.14	June	1	11.57	Oct.	15	11.46
Feb.	*11*	*12.14½*	*June*	*15*	*12.00*	*Nov.*	*3*	*11.43*
March	*1*	*12.12*	*July*	*1*	*12.03*	*Nov.*	*16*	*11.44*
March	*15*	*12.09*	*July*	*15*	*12.05*	*Dec.*	*1*	*11.49*
April	*1*	*12.04*	*July*	*26*	*12.06*	*Dec.*	*15*	*11.55*
April	15	12.00	Aug.	15	12·04	Dec.	25	12.00
			Aug.	31	12.00			

As you see, on four days, viz. April 15, June 15, August 31 and December 25, mean and true solar time coincide. On February 11 the equation of time is no less than 14½ minutes, on November 3 so much as 17 minutes.

At one time opponents of the B.S.T. (British Summer Time) thought they could gain their cause by stressing the "unnatural" element in this arbitrary way of regulating time, arguing that "when the sun is seen due South it is 12 o'clock and any regulation violating this fundamental truth is contrary to nature." Our list of times tells its own story and clearly shows how they erred.

Our way of regulating the time is as ingenious as it is artificial and *must of necessity be so.* In the first place, the time of a given meridian must be made universal for the whole country, and thus conscious errors are made. In the second place, mean time instead of true solar time has to be adopted, when fresh errors are added to the others, on this occasion of more than a quarter of an hour. The reproach of artificiality, therefore, may never be made; any regulation of time must be artificial and may not adopt the true solar time (still less the true local solar time), for fear of becoming impracticable. That system is best which, besides being

practical, meets the requirements of everyday life as much as possible. And since the majority of people get up after sunrise during a considerable part of the year and go to bed after sunset practically throughout the year, in other words shift their "civil" noon towards the evening hours of the clock, it is useful either to introduce a summer time or to choose a meridian lying well East of us for the computation of time.

The Earth's Revolution Round the Sun

The Earth rotates on its axis in one day, and revolves about the sun in one year in an elliptical orbit which differs only little from a circle.

The length of the Earth's orbit round the sun is about 580,000,000 miles. The Earth covers this distance in about 365 days and 6 hours, that is at the rate of more than 18½ miles per second, a velocity vastly exceeding that of the rotation even at the Equator. This movement, too, is imperceptible on Earth for the same reasons as given in the case of the axial rotation. We may even say that since it is quite the same wherever we are on earth, we are still less aware of it than of the axial rotation.

The exact duration of the so-called tropical year[1] is 365 days 5 hours 48 minutes and 46 seconds, hence not a whole number of days. And since, for our calendar year, we want a whole number of days, we are here faced with a nasty problem: the adaptation of our social year to the true tropical year, a problem which has even become famous in the history of mankind. Let us now look at it somewhat more closely.

The Calendar

What is at once clear is that to give the year a fixed number of days is out of the question. Should we take 365 days, the year would be a quarter day too short; we should then, in four years, be one day ahead of the actual

[1] *See* page 82.

date, and after 720 years people would be able to skate in July. Such a regulation of the year is therefore impracticable —a system is wanted by which the seasons keep their fixed places in the calendar.

As soon as the length of a year had been found to be 365¼ days the most obvious course was to introduce a year of 365 days, an extra day being given to every fourth year (leap year). It was Julius Cæsar who introduced this arrangement—the Julian Calendar—in the Roman Empire. The idea probably originated in Egypt. In the days of Julius Cæsar it was high time that an end should be put to the existing confusion in the regulation of time. The first of January had been carried back nearly as far as the autumnal equinox, i.e. to the point where the first half of October "ought" to be. Cæsar, therefore, gave a length of 445 days to the third year of his consulate (46 B.C.). January 1 was thereby restored to its former place (in so far as this term may here be applied).

The Julian calendar was a marked improvement. The seasons were now practically marked off by fixed dates, but the arrangement was not quite perfect. For in adopting the 365¼ day arrangement the year is taken too long by more than 11 minutes, so that there is an unavoidable time-lag of about three-quarters of an hour in four years; this is about three-quarters of a day in a century. This had accumulated to ten days by the time Pope Gregory XIII took the initiative in reforming the calendar in 1582. This new calendar, named the Gregorian Calendar after that patriarch, is still in use. He began by suppressing ten days in 1582, so that there was a sudden jump from 4th to 15th October. Further, the following correction to the Julian calendar was devised: a centurial year would be no leap year, except once in four centuries, viz. in 1600, 2000, 2400, etc.; 1700, 1800, 1900 were therefore to be no leap years. The Gregorian calendar met with a good deal of opposition; introduction of it was easy in Roman Catholic countries, owing to the Pope's authority, but the English nation did not adopt the reform

introduced by Pope Gregory until 1752; the calendar was then 11 days wrong. The required correction was made by omitting the days between 2nd and 14th September. Holland adopted the New Style in 1700, Switzerland in 1701, Sweden in 1753, the countries belonging to the Greek Church not until 1918 and Turkey as late as 1927. The difference with the Julian calendar had meanwhile amounted to 13 days.

The difference is now practically righted, but yet not altogether.[1] At the present moment we are slightly in arrear and the discrepancy increases, but so slowly as to be almost negligible. Before 4,000 years have elapsed we shall have to omit one leap day!

If we may safely say that the Gregorian calendar has admirably reconciled the civil year with the solar year, yet in a number of respects it leaves much to be desired. The year is divided into twelve months (each about the length of a lunar revolution and originally derived from it), varying from 28 to 31 days, and at the same time numbers 52 weeks (each about $\frac{1}{4}$ of a lunar revolution and perhaps in origin related to it). A month may contain 4 weeks (February) or 4 weeks plus a fragment of a week or 3 or 4 weeks plus two fragments. A month may have 4 or 5 Sundays and 24 to 27 weekdays. Dates differ one day of the week from year to year and two days in a leap year. Easter, and hence Ascension and Whitsuntide, too, may shift as much as 34 days, for Easter falls on the first Sunday after the calendar full moon on or after March 21. A year may have 52 or 53 Sundays and 3 or 2 festivals besides. The quarters number successively 90, 91, 92 and 92 days, the half-years 181 and 184 days. The shortest month is February, a last remnant from Roman antiquity, when the year commenced on March 1 and the remaining days were given to the last month of the year (February). This beginning on March 1 also explains the names of Septem-, Octo-, Novem-, Decem-ber, which are

[1] The mean Julian year has a length of 365·25 days; the mean Gregorian year of 365·2425 days; the tropical year lasts 365·242216 days.

simply the Latin words for seven, eight, nine, ten with the suffix "ber." Such is, briefly, the strange muddle of our present calendar. For statistical purposes it is exceedingly inconvenient, which we could prove with numbers of examples. However, we must not wander too far, but must return to our subject.

The Reform of the Calendar

It should here be mentioned that important plans for reforming the calendar have been put forward and have been enquired into by a special committee of the League of Nations. There are a great number of them; but to me the scheme which seems most attractive divides the year as follows:

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	blank
31	30	30	31	30	30	31	30	30	31	30	30	day

The quarters are of equal length and all begin with a Sunday. This calendar is *perpetual*, i.e. the same for every year. In every year the same date falls on the same day. This is achieved by intercalating a blank day (New Year's Eve) at the end of the year. This day forms no part of any week or month.

The order then becomes: Saturday December 30, New Year's Eve, Sunday January 1. In a leap year another blank leap day is interpolated between June 30 and July 1.

Easter is, for instance, always on the second Sunday in April; Ascension Day and Whitsuntide are then fixed at the same time.

No doubt such a reformation of the calendar would be of great help to statisticians. The fixation of Easter may even be regarded as an urgent matter and will very likely be brought about. But the other changes, notably the blank day and the *perpetual calendar* depending on it, seem to have less chance of success. Opposition to this reformation has been particularly strong on the part of orthodox Jews. This is not at all surprising if we remember that

should they *not* intercalate the "blank" day in their calendar (which is well known for its many deviations) their Sabbath, every time a blank is inserted, would retrograde one day and subsequently fall on Friday, Thursday, Wednesday, etc. This, no doubt, would mean a serious disadvantage to them. Still, to my mind, their opposition is unfounded. For I cannot see that the insertion of a blank day should be a greater obstacle to the orthodox Jews than to the orthodox Christians or Mohammedans. I would propose the following compromise, which, so far as I know, has not been suggested before:

Let the orthodox Jews disagree with the blank day for a period of five years; these, I admit, will be difficult years in many respects, but at the end of that period (provided it contains one leap year) Sabbath and Sunday will coincide. If from that day onwards the orthodox Jews adopt the blank day, Sabbath and Sunday will for ever be observed on the same day; this would both be in the interest of a proper observance of the Sabbath by orthodox Jews and in the interest of society in general.

Proofs of the Earth's Revolution about the Sun

Let us now return to our Earth's revolution about the sun. Can this movement be proved in a simple way?

The answer is yes. The very first proof we are able to give is a so-called indirect proof, that is to say: we can show that, if the Earth did *not* revolve about the sun, the celestial phenomena would be quite unintelligible. We must, to this end, like the ancients and, for that matter, the astronomers of even the sixteenth century, suppose the Earth at rest. Should the Earth not revolve round the sun, there is only one alternative to explain a large number of very important phenomena (for instance, the alternation of the seasons, the difference between sidereal and solar day): we must then assume that the sun revolves about the Earth in one year. But the same objection may be raised to this supposition as was done when we dealt with the axial rotation: it

would mean that the movements of a giant are governed by those of a dwarf. Nor is this all. We shall see further on that there are nine different heavenly bodies turning about the sun, at different distances. The further we get from the *sun, the larger the orbits and the longer the time a revolution takes. These nine heavenly bodies are the **planets** and it will be seen that the Earth is one of them. The revolving of all these planets about the sun at widely varying distances* and speeds causes the place of these planets in regard to the moving Earth to be continually subject to variations which are the result both of the movement of the planet itself and of the Earth. Now, if the Earth is indeed one of those planets and, like any one of them, revolves about the sun, all those alterations and variations can be explained in a very simple way and—which is still more important—be *predicted* with the greatest accuracy imaginable. If we, however, suppose the Earth at rest, it is a perfectly hopeless task to try to design orbits for the other planets to fit in with our observations. And if it be attempted at all, the result is an extremely complicated system of movements, which defy all efforts to square them with actual observation. Accordingly, astronomers who, in principle, wanted to maintain the *Ptolemaic*[1] system in which the Earth is supposed at rest, were obliged to have recourse to more and more complicated constructions. And they were never quite successful. One of them declared that he was at a loss to see why God should have made the world so complicated.

In 1507 Copernicus (1473–1543) came to the conviction that the Earth revolved about the sun,[2] a theory which settled all difficulties at one stroke; for now the movements of the planets were intelligible.

Summarizing, we may say that if we assume the sun to

[1] Ptolemy flourished in the second century A.D. He lived in Alexandria and wrote a number of famous books, among others the big *Handbook on Astronomy*. This work, written in the Greek language, was translated into Arabic as the *Almagest*, the authority of which in the science of astronomy was unchallenged until the sixteenth century.

[2] Some Greek scientists of remote antiquity had already advanced this theory. But the time was then not yet ripe for such audacious ideas.

revolve about the Earth, the planetary system becomes an absurdity; hence our point of view must be false, the Earth must revolve about the sun.

No reader, however, need be satisfied with this indirect *proof; there is also* ***proof positive.*** *We shall here give two examples. The most famous is probably that concerned with the so-called "parallax" of the stars, and we shall start* by giving an explanation of this phenomenon.

The Parallax of the Stars

If, standing somewhere near a tree, I move to the right, the tree seems to be shifted in the opposite direction, that is to the left. This is most clearly noticeable if behind the tree a distant object—a church tower, the moon or a star —can be observed. Whilst moving ourselves to the right, we see the tree passing in the opposite direction across the tower, the moon or the star. One might, of course, with equal right stress the other side of the matter and say that the tower, the moon or the star *moves with us* in the same direction behind the top of the tree.

However, we are now primarily concerned with the first aspect of the phenomenon.

It is a splendid starlit night and there is a church spire near. At a distance of about 300 feet from the foot of the tower I begin to walk around it in a circle, with my eye fixed on a ball at the top of the steeple. I see the ball as a black mark against the faintly luminous sky. Now while moving in a circle to the right (my face to the steeple), I see the dark ball travel to the left across the sky, in its apparent course continually hiding stars from my view. I now try to remember the stars which are successively covered and, after completing my circle, I stop a moment to look at the places occupied by those stars. I find that the ball at the top of the steeple has also described a *circle* in the sky during my walk. It need hardly be said that this circle will be larger as the steeple is lower, and smaller as the steeple is higher.

Well, if it is true that the Earth revolves around the sun, the above phenomenon must be noticeable in its rotation; the stars must then, to our eye, describe circles in the vault of heaven. Copernicus's adversaries triumphantly declared that nothing of the kind was noticeable, so that his theories could not be right. Of course, *if* the stars showed such movements, they would own themselves beaten, but as long as

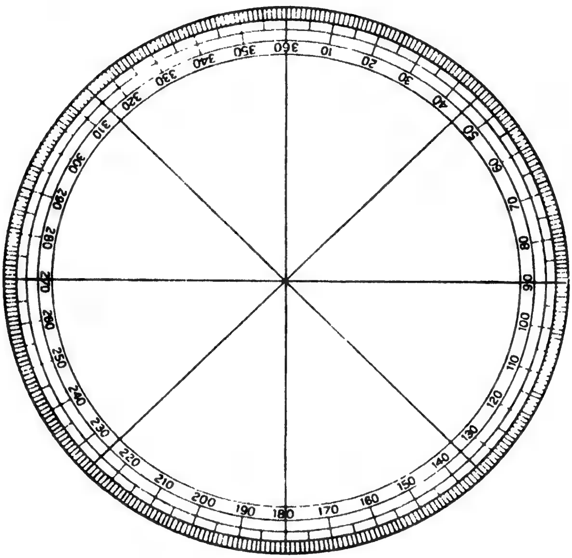


Fig. 8
Division of the circumference of the circle into 360 degrees.

this was not the case, Copernicus was obviously wrong. The only reply Copernicus's followers could give was that evidently the stars were at such great distances from us that the apparent circles they described in the sky were too small to be observed by means of the then available instruments and telescopes. They could only hope for better times, when perfected instruments would make it possible to prove that this phenomenon occurs. One must admit that such a counter-argument, at *that* moment, was weak. The hopes of Copernicus's followers, however, were brilliantly

fulfilled. When, much later, in the nineteenth century, telescopes had been improved, the first star circles or parallaxes were soon discovered. First, of course, with the nearest —or rather, least remote—stars. The place of a star which was suspected to be near was compared with that of another star which was seen close to the preceding one, but which one had good reason to suppose at a great distance. The angle between those two stars was determined with the greatest accuracy. The same operations were repeated *half* a year later, when the Earth had moved away as far as possible in its orbit from the first point. Success was not

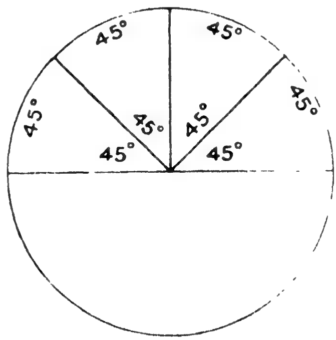


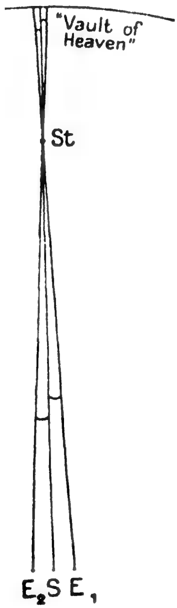
Fig. 8A

slow in coming. The German astronomer Bessel, in 1842, succeeded in determining the first "change of angle." It was that of star 61 of the constellation Cygnus (Swan). He found a change in angle of $\frac{62}{100}$ second of arc, or a little more than half a second of arc.

What is a second of arc? A circle is divided into 360 degrees (*see* Fig. 8). Hence a half-circle is 180 degrees (written: 180°). A quarter of a circle or a right-angle is 90°. If we halve this angle, we obtain two angles each of 45° (Fig. 8A). The line bisecting the right-angle also divides the corresponding quarter of the circumference of the circle into two arcs of 45° each.

It will now be clear that the arc of heaven from horizon to horizon is 180°. The "top" of the sky over our heads,

called Zenith, is at a distance of 90° from the horizon. A heavenly body half-way between horizon and Zenith is therefore at 45° above the horizon and also at 45° from the Zenith. It is easy to see that a distance of one degree in the sky is not much to our eye. The apparent diameter of the sun and the moon (to our eye the sun and the moon are of equal size) is about half a degree. A degree is subdivided into 60



St = Star.
S = Sun.
E_1 Earth at a given date.
E_2 Earth half a year later.
St_1 Apparent place of star in the "Vault of Heaven" on first date.
St_2 Apparent place of star in the "Vault of Heaven" on second date.
⌣ and ⌢ show the angles indicating the parallax of the star.

minutes (′); a minute into 60 seconds (″). What a tiny little distance in the sky a second of arc must be! Not more than about $\frac{1}{2000}$ part of the apparent diameter of the sun or the moon! The measuring of an angle of one second, therefore, is already a matter of delicacy. Astronomers nowadays *use* hundredths, nay, even thousandths of seconds of arc. As we have seen, Bessel found for star 61 of Cygnus a change of angle of $\frac{62}{100}$ second of arc. Half of this angle, or 0·31″, is called the *parallax* of the star; it is the angle which the radius (that is, half the diameter) of the Earth's orbit round the sun presents

when viewed from the star (*see* Fig. 9). From the *parallax* the distance of the star is easy to find by a simple calculation, if only the radius of the Earth's orbit is accurately known. The *smaller* the parallax, the *greater* the distance. The biggest parallax of any star that has yet been observed is about ¾ second of arc. At first astronomers only succeeded in determining the parallax of some 20 or 30 stars; later on this number was enlarged to some hundreds and in recent times the parallaxes of some thousands of stars have been determined. But in the majority of cases the parallax remained infinitesimal, so far distant did the stars prove to be from us. I shall revert to this subject at length. The main thing is, however, that, at any rate with the nearest stars, the star circles were proved to exist, so that consequently Copernicus's antagonists had lost their last argument, and the movement of the Earth about the sun could be shown by direct evidence.

The Aberration of Light

We have now come to a second, equally remarkable proof. When in perfectly calm weather it rains, the drops or jets of rain come down straight. But if I walk rapidly through the rain, the direction of the rain seems to be changed as a result of my movement, and if I run fast the rain strikes me in the face. If now I want to keep dry I must tilt my umbrella slightly forward. My forward movement and the falling down of the rain have combined into one single motion, causing the drops of rain to hit my body obliquely. If I sit in a train the raindrops as seen through the window fall in an oblique direction; if the train is travelling at full speed its movement is so great in relation to the rate at which the drops fall that the jets of rain seem to "fall" nearly horizontally instead of perpendicularly.

An analogous phenomenon is noticed with respect to the rays of light reaching our Earth from a star. If we were to direct our umbrella, in this case the telescope in which we want to receive the light, with absolute accuracy

towards the star emitting it, we should not be able to receive those rays. The Earth's speed in its orbit is great enough in relation to the velocity of the light (even though it is one 10,000th part of it) to produce a perceptible, though slight, deflection. The star, consequently, is not exactly where it seems to be. This phenomenon is called "aberration" (straying from the path) of the light, and its existence is a direct proof of the Earth's movement round the sun. It, too, causes the star to describe an apparent small "circle" in the sky every year; for does not the Earth's movement round the sun continually change its direction? The circle is even much larger here than that consequent upon the *parallax*. When the occurrence of these circles was discovered, people thought at first that they had found the long-looked-for parallax. Very soon, however, this proved not to be so; the true nature of the phenomenon was identified, and the genuine, much smaller *parallax* was not discovered until years and years afterwards. Although at first the new discovery caused some considerable disappointment, yet it is of the utmost importance, inasmuch as it corresponds in the smallest details with what scientific theories based on the supposed movement of the Earth at the supposed rate led one to expect. Hence this phenomenon, too, constitutes a complete proof of the Earth's movement round the sun.[1]

The Alternation of the Seasons

We are now going to deal with what must be considered as the most important of all phenomena, notably the alternation of the seasons—spring, summer, autumn and winter. Besides the Earth's movement round the sun, its axial rotation and the inclination of the axis cause this alternation.

We are fully convinced of the reader's keen interest in this matter, of his eagerness to know the ins and outs of it, and to see through the rather knotty problem of how the

[1] A third proof may be deduced from the "Doppler effect." *See* page 294 note 1.

seasons come to exist. It will require a good deal of attention and patience on his part, but we have no doubt that in the end he will find his trouble amply rewarded.

To make everything quite clear a model is essential. We shall make this ourselves, in our minds. To this end we go into a square room having walls 7 feet long. We number the walls, anti-clockwise, 1, 2, 3 and 4. With

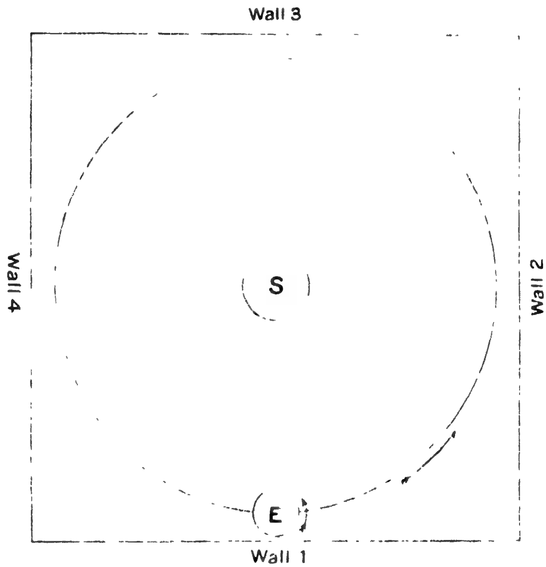


Fig. 10

the middle of the room as centre we now draw on the floor a circle with a radius of about 3 feet, which will almost touch the walls. Round the central point we make a hole in the floor having the shape of a hemisphere with a radius of 6 inches. In this hole we place a ball of the same radius, so that it fits exactly in the hole, its upper half protruding above the floor. This is our sun. Further we buy a small Earth with a radius of 4 inches. Round the point on the circle nearest to wall No. 1 (E Fig. 10) we make another hemispherical hole with a radius of 4 inches, in which our

Earth is placed. This, too, fits exactly with its upper half sticking out. Our model is now almost complete. Let me add at once that it contains a number of inaccuracies. The proportion in size between Earth and sun is altogether wrong and in relation to the distance between them their sizes have been taken far too large. Besides this, neither the real Earth nor the real sun is a true sphere, while the *Earth's orbit round the sun is in reality not exactly a circle. Never mind, the model will do quite well for our present purpose. We shall presently see how, by its means, we can quite satisfactorily solve all our problems.* We now first of all see to it that our model can work properly. Our Earth, for instance, must be able to move round the sun, and making this possible requires quite a lot of work. A track has to be made in the floor for the Earth to move in; some kind of clockwork has to be fitted somewhere to keep things going, but this is quickly done, in our imagination. The Earth can now revolve round the sun, and its orbit is in exactly the same plane as the floor. This plane, for reasons which will be explained afterwards, we shall call "ecliptic." The Earth's movement round the sun, in our model, takes place anti-clockwise (*see* Fig. 10).

We just now placed our Earth in its hemispherical hole without heeding in the least in what position it finally came to lie. But a moment's thought will make it clear to you that it may take up an endless variety of positions; any country or sea may lie on top. It stands to reason that the real position of the Earth should be imitated. But what is this position? We do not know yet. And because we do not know we shall probably be inclined to place the Earth so as to have the North Pole right at the top. The equator will then be flush with the floor, the South Pole in the middle under the floor, while the Earth's axis will be at right-angles to the plane of the floor, hence perpendicular to the ecliptic.

To avoid possible misunderstanding, let me here at once point out that, as will be seen further on, the Earth's axis

in reality is not perpendicular to the ecliptic, but is *oblique*. However, it is well first to ascertain what phenomena would occur if the axis were perpendicular.

We must now first fit another mechanism into our model, permitting the Earth to rotate round its axis. This mechanism is started at a slow rate, while as yet the Earth's movement round the sun is not switched on. Consequently, *the Earth, while rotating slowly, does not move from its place. We now make a final alteration to the model: the sun is replaced by a hollow glass sphere with a lamp burning* inside. All other lights in the room are now switched off.

If the Earth's Axis were Perpendicular . . .

The sun's rays strike the Earth's surface from a direction perpendicular to its axis. We can assume those rays—considering the immense distance the sun is in reality away from us—to be parallel to each other. What will now be the aspect of the stage upon which the human drama is enacted? To find this out we shall successively examine three points of the Earth's surface. Let us first take the North Pole. The plane on which the scene of life is staged at the North Pole, that is, the plane of the horizon of the North Pole, is at right-angles to the axis. We take a stiff postcard and pin it on to our North Pole perpendicular to our Earth's axis. Consequently the plane of the horizon of the inhabitants of the North Pole is now parallel to the floor of the room, hence parallel to the ecliptic. A man standing upright at the North Pole is perpendicular to that plane. The sun's rays strike the Earth in a direction parallel to the ecliptic. At the North Pole the sun will now be exactly on the horizon, i.e. about one half of it will protrude above it. Now, if (still in our model) we look at the sun across the postcard, with our eye on a level with the card, we can just see the top part of the sun. The Earth in our model rotates round a perpendicular axis, also anti-clockwise. Now what happens at the Pole? The sun neither rises nor sets there, but makes a complete round of the horizon in

slightly less than 24 hours, without moving upwards or downwards at all. And now, what will happen if we set our Earth travelling round the sun? Reason tells us that *nothing* can change and indeed, as we see our Earth revolve about the sun, our supposition is fully borne out by the facts. The sun keeps moving round the horizon at the Pole. Only, it will now be slightly longer before the sun has returned to the same place on the horizon. The latter phenomenon has already been dealt with.

We now leave the North Pole, taking our plane of the horizon (the postcard) with us, and go to the Equator. The whole model, sun and Earth alike, are raised about eight inches above the floor, otherwise we cannot properly observe what happens at the Equator. For the rest everything is left as it is. We now pin our postcard on to some spot on the Equator, e.g. Pontianak in the island of Borneo. The postcard, now representing the plane of the horizon at Pontianak, is perpendicular to the radius connecting Pontianak with the centre of the Earth. It need hardly be explained that this radius is parallel to the floor, and that our postcard is parallel to the Earth's axis and perpendicular to the floor, and hence perpendicular to the ecliptic. We now again set the Earth rotating round its axis and observe that during one rotation the sun successively appears *on the eastern horizon, rises straight up into the sky, shooting down perpendicular rays of heat from its zenith, and finally sinks straight down behind the western horizon. Night has set in, a night of exactly the same length as the day.* We again set the Earth revolving about the sun and again we see that no change is brought about, except for a slight extension of the day.

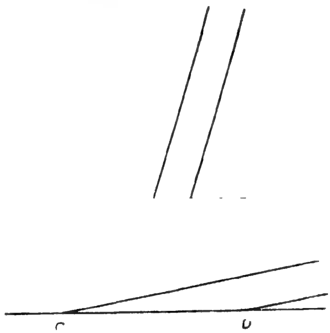
Finally, we take a point half-way between the Equator and the North Pole, hence on the 45th degree of latitude (the Equator is 0°, the Pole 90°, for the Earth's axis is perpendicular to the plane of the Equator). We choose Turin, in Italy, and begin by pinning our plane of the horizon on to the spot in question. This plane, it is easy to see, is at

an angle of 45° to the floor. We can now accurately observe the phenomena which would occur in Turin if the Earth's axis were perpendicular to the ecliptic. The sun rises in the East, ascends obliquely until it takes up a position at 45° in the vault of heaven and descends obliquely towards the western horizon, where it sets exactly 12 hours after sunrise. Here, too, therefore, night and day are of equal length. The reader can now easily try out intermediate points, for instance London, situated near the 52nd parallel of latitude, where the phenomena witnessed at Turin will practically be repeated, with this difference that the sun will not get higher than 38° above the horizon. And we shall invariably find that day after day the phenomenon is exactly repeated, in other words, that the Earth's revolution about the sun makes no difference (except for the small extension of the day).

Needless to say, conditions are exactly the same on the Southern hemisphere. Only, at noon the sun is there not in the South, but in the North. This, too, can be verified by means of our model.

What is now clear is that, if the Earth's axis were perpendicular to the ecliptic there would be no alternation of the seasons; conditions would be perfectly the same throughout the year. The Earth would then be divided into "climate zones." At the Equator things would then not differ very much from what they are in reality; the sun would there be straight over our heads at noon · hence it would be scorching hot. At the Poles the sun would float on the horizon throughout the year; the sun's rays would never be hot there. For, we all know, the lower the sun, the less heat it gives. This well-known phenomenon has two causes. In the first place, the same beam of sunlight is spread out over a larger distance, according as it strikes the Earth's surface more obliquely (Fig. 11 makes this clear). Hence, when the sun is low a square yard of the Earth's surface will receive a smaller portion of sunlight than when the sun is high in the sky. In addition to this, our atmosphere

arrests part of the sun's rays, weakens them. The longer the road they have to cover through the atmosphere, the more they are weakened. And, the lower the sun is in the sky, the longer the air path (*see* Fig. 12). It follows that



The Earth's surface is heated less according as the sun is lower. A beam of sunlight is extended over the distance AB when it strikes the Earth almost perpendicularly. The same beam is spread out over the distance CD if it strikes the Earth more obliquely.

the Poles at a perpendicular position of the Earth's axis will be, as they are now, the cold regions. The long arctic night and the long arctic day, each lasting half a year, as they now exist on Earth, would be impossible if the Earth's

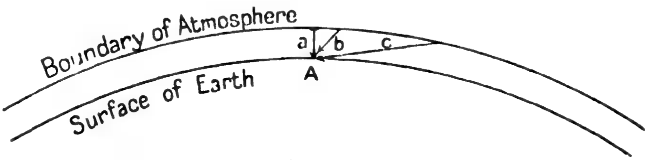


Fig. 12

Weakening of the effect of the sun's rays when the sun is low, owing to the longer road travel through the atmosphere.

a—Path of a perpendicular ray through atmosphere.
b—Path of an oblique ray through atmosphere (sun is lower).
c—Path of a still more oblique ray through atmosphere (sun very low).

axis were perpendicular. We might then say that there was a kind of eternal dawn at the Poles. From the Equator to the Poles the temperature would gradually decrease. About half-way, hence also in our country, the climate would be delightful, not too hot, not too cold. It would be *eternal spring* in the most literal sense of the word. Again, no

alternation of seasons. And everywhere on Earth (except for the immediate surroundings of the Poles) day and night, throughout the year, would each last 12 hours.

We must observe in passing that these conditions correspond in a large measure with the existing ones at the vernal and autumnal equinoxes, about March 21 and September 22.

On those days, the sun's midday rays strike the Equator perpendicularly, the sun at the Poles makes a round of the horizon in the same way as we have seen above, while everywhere on Earth day and night are of equal length. *This correspondence cannot be accidental. We shall presently explain the why and the wherefore of it.*

The Earth's Axis is Oblique

We have just seen what would happen if the Earth's axis were perpendicular to the ecliptic. It does not represent things as they are, for in reality the axis slants. And, curiously enough, this one fact at one stroke explains the whole mysterious complex of phenomena presented by the alternation of the seasons as we know it. This explanation we are now going to give. Let us return to our model. Our first difficulty is at what angle to place our Earth in its hemispherical hole near the wall? We begin by again placing it so that the North Pole is right at the top. The Earth's axis is then perpendicular to the floor, that is, to the ecliptic, or in other words, it makes with the ecliptic an angle of 90°. But in reality this is not so; the Earth's axis is inclined to the ecliptic at an angle of about 66½°. Hence in our model we must turn the North Pole towards the ecliptic over an angle of 23½°. But in what direction? We can do this in *any* direction. All points to which we can depress the North Pole over an angle of 23½° lie on a circle parallel to the ecliptic. Let us for one moment leave the Earth in its original position with the North Pole upwards; we can then see that circle on our globe, it is the Arctic Circle. The Earth may be inclined in the direction of any point on

that circle! And, actually, we *may* incline our Earth in any desired direction; only, the direction we choose will determine the date of the year our model represents. If *we move the Pole exactly in the direction of the sun, the Earth will be in its position as on June 21.* If the opposite direction is chosen, we get the position as on December 21. If, standing with our back against wall No. 1, we turn the *Pole to the left, at right-angles to the first direction, we get March 21; to the right, September 22. The intermediate directions give the intermediate dates.*

December 21

But we must make up our minds which one to take and we choose December 21. We therefore incline the Pole over an angle of $23\frac{1}{2}°$ towards wall 1, hence in a direction opposite to the sun. The Earth's axis has now a distinctly oblique position, it inclines to the ecliptic (the floor) at an angle of $66\frac{1}{2}°$. We now again raise the sun and the Earth slightly above the floor, without making any other changes. The sun is relighted and the Earth set rotating, but not as yet revolving round the sun. What do we see now? That the North Pole is enveloped in darkness. Whatever number of rotations the Earth makes, the sun's rays cannot get at the Pole. They do not reach beyond the point which was just now taken up by the North Pole, which is now $23\frac{1}{2}°$ away from the Pole. If we draw a circle round the Pole at $23\frac{1}{2}°$, it is night within that circle. This circle is the Arctic Circle and everything within it is in continual darkness. Everything we have said can be verified in Fig. 13. At the South Pole the reverse happens; everything is bathed in sunlight; if we pin our plane of the horizon (the postcard) on to the South Pole, we see that the sun circles round the heavens at an altitude of $23\frac{1}{2}°$ above the horizon. This is rather high, a good deal higher than the sun's altitude in our country at 12 o'clock in mid-winter. The day is long at the South Pole and would be eternal if the Earth should remain stationary. We further observe that the territory

round the South Pole where the sun does not set, is also enclosed in a circle at $23\frac{1}{2}°$ from that Pole. This is the southern polar circle, commonly called *Antarctic Circle.*

And what about the Equator? Let us first put our plane of the horizon in position as we did before. It then becomes evident, on setting the Earth rotating round its axis, that day and night at the Equator are of equal length, notably, 12 hours. At the same time we notice that at *12 o'clock the sun is very high in the southern sky, but by no means at the Zenith; actually, it is not more than* $66\frac{1}{2}°$ above the horizon (that is, exactly the angle of inclination the axis makes with the ecliptic! This is quite natural if we remember that the plane of the horizon of the Equator is parallel to the Earth's axis). (*See* Fig. 13.) As you see, at the Equator the sun is by no means always at the Zenith at 12 o'clock—the difference may be quite considerable. On June 21 the sun, in London, is about $61\frac{1}{2}°$ above the horizon; in Pontianak on December 21 at $66\frac{1}{2}°$, hence not very much higher.

We shall now direct our attention to another part of the Earth's surface. We choose a point $23\frac{1}{2}°$ South of the Equator, for instance Rio de Janeiro, and affix our plane of the horizon to it. The day is now seen to be longer than the night; from sunrise to sunset is about $13\frac{1}{2}$ hours, from sunset to sunrise about $10\frac{1}{2}$ hours. We see the sun rise in the East—or, more accurately, in the East-South-East—ascend steeply but not perpendicularly until it reaches the Zenith at exactly 12 o'clock, after which it descends, setting in the West-South-West. This, on December 21, not only holds good for Rio de Janeiro, but applies to all places in Latitude $23\frac{1}{2}°$ S. All these places lie on what is known as the *Tropic of Capricorn.*

The Tropics

Why the name *tropic?* To understand this properly, you should first of all know that the word tropic is derived from a Greek verb meaning "to turn." Let us just assume

for a moment that we are somewhere on the Tropic of Capricorn. We shall then, from June 21 to December 21, see the sun higher in the Northern sky every day, until on December 21 it reaches the Zenith.[1] One might now be

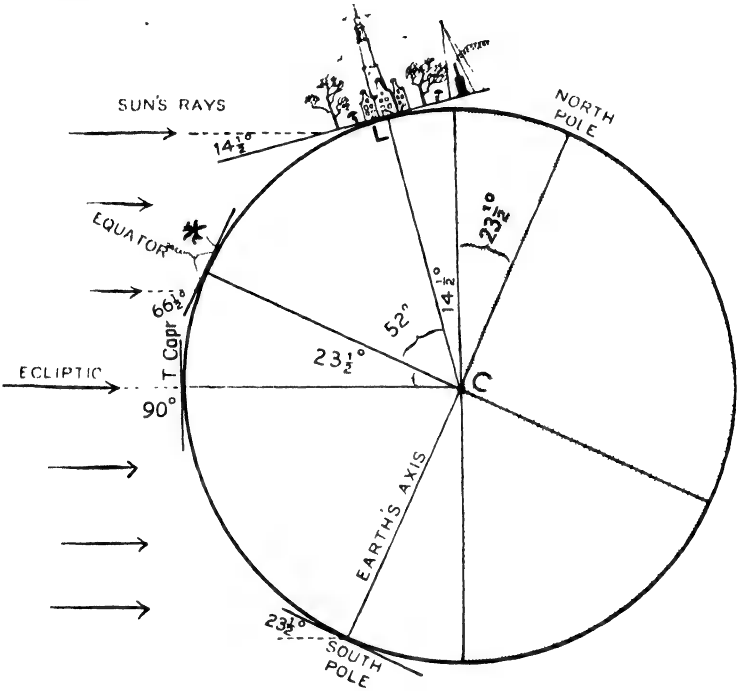


Fig. 13

The Earth on December 21 at twelve o'clock (noon) Greenwich mean time. Winter on the northern hemisphere.

L.– London. T. Capr.—Point on Tropic of Capricorn. The North Pole is turned away from the sun. At the equator the sun is in the South. On the Tropic of Capricorn the sun is at th

day and a long night. On the Southern hemisphere reverse conditions prevail. Sun's altitude: in London 14½°; at the equator 66½°; at the South Pole 23½. The observer in our room i

led to think that the sun would begin to descend towards the Southern half of the heavens. But this is not so; after December 21 the sun gradually *returns* to the North. What

[1] The sun is then "in the Sign" of Capricorn, hence the name of Tropic of Capricorn. (*See* page 174.)

the Tropic of Capricorn is in Latitude 23½° S., the Tropic of Cancer is in Latitude 23½° N. (these angles of 23½° are equal to the obliquity of the Earth's axis, that is its departure from the perpendicular). Needless to say, conditions on the Tropic of Cancer are exactly the reverse of those obtaining on the Tropic of Capricorn. At Havana, for instance, which is on the Tropic of Cancer, the sun's altitude at noon in the South increases from December 21 to June 21, when it reaches the Zenith,[1] after which it gradually returns to the South.

Length of Day and Night on December 21

But let us return to our December 21. There is a good deal more to be discovered on it. While our Earth is spinning we observe that from North to South the days are continually drawing out and consequently the nights shortening. North of Latitude 66½° N. there is no daylight at all, only night (apart from some twilight in the middle of the day so long as we are not too far North of the polar circle). Somewhat more to the South the sun just peeps over the horizon at noon, upon which it disappears almost at once. Already, in Latitude 65° N., there is daylight for 2 hours and 51 minutes as against a night of 21 hours and 9 minutes; in Latitude 60° N. there is daylight for 5½ hours, in Latitude 50° N. for almost 8 hours, in Latitude 15° N. for more than 11 hours, in Latitude 5° N. for 11 hours and 43 minutes, and at the Equator, as we know, exactly twelve hours. Obviously, on the Southern hemisphere we get the exact reverse of Northern conditions; on December 21 the day is longer as we proceed southward:

in Latitude 5° S.—12 hours and 17 minutes;
" 20° S.—13 hours and 13 minutes;
" 40° S.—almost 15 hours;
" 50° S.—over 16 hours;
" 60° S.—18½ hours;

while south of 66½° there is no night at all. Such, then, is the state of affairs on December 21.

[1] It is then "in the Sign" of Cancer.

But we have not finished yet. Anywhere on earth we can measure the sun's altitude at noon, that is its meridian altitude. We have already done this for the Equator and the Tropic of Capricorn, but are now going to do it for London. The plane of the horizon is first pinned on to London. The sun rises somewhere about the South-East slightly after 8 a.m., and ascends very slowly. At noon it is at its culminating point (which is not the Zenith). But how low this is in the sky! We can see it in our drawing (Fig. 13) at a glance: what a small angle between the direction of the sun's rays (ecliptic) and the horizon of London! It *should be borne in mind that in connection with the immense distance to the sun, all sun's rays may be regarded as being parallel to the ecliptic. The meridian altitude of the sun in London on December 21 is now easy to calculate.* London is, roughly, in Latitude 52° N. The difference between this angle of 52° and the angle of inclination of the Earth's axis (66½°) supplies the answer, and on December 21 the sun cannot ascend in London beyond 14½° above the horizon, that is, less than one-sixth part of the arc from horizon to Zenith.

Optical Illusion near the Horizon

It *seems* to be much more, about a quarter or even a third. If you ask the man in the street to give an estimate, he will invariably make a wrong guess. He is labouring under an *optical illusion.* We all have a tendency to over-estimate stretches of sky (in degrees of arc) near the horizon and to under-estimate them near the Zenith. That is why the sun and the moon seem to be much larger near the horizon than high up in the sky; constellations, too, have a more spread-out appearance when seen near the horizon. But all this is nothing but optical illusion.[1] We can easily satisfy

[1] This optical illusion may be explained as follows. We know, from long experience, that an object which we see low on the horizon, a church steeple, for instance, is far away from us. To this object, therefore, we apply, partly subconsciously, a different measure, seeing it large in our minds. Now, if the moon rises behind that church steeple, we do the same, but we no longer do it when the moon is high in the heavens.

ourselves of the truth of this by taking a threepenny bit between our fingers and stretching our arm slowly until the coin exactly covers the moon. To the surprise of many, an ordinary arm's length will not suffice; the coin must be held at a distance of about six feet from the eye, and an assistant is therefore wanted. We make the experiment when the moon is very high in the heavens, and repeat it when the moon is close to the horizon. It then transpires that in both cases the coin must be held at the same distance from the eye. This, of course, could never be so if the moon were larger near the horizon, that is, if it took up a larger visual angle near the horizon than high in the heavens.[1]

After this short digression we return for the last time to our December 21. The meridian altitude of the sun on that date increases from the Northern polar circle to the Tropic of Capricorn from 0° to 90° and decreases from there to the South Pole from 90° to 23½°.

We now set our Earth revolving about the sun. In half a year (in our model in a few moments) the Earth has moved from wall No. 1 to the opposite wall No. 3. *But during this displacement the Earth's axis keeps pointing in exactly the same direction into Space. And this is the key to the secret.* Keep hold of this key and you will be able to unravel any mystery you may come across. The walls of our room suddenly appear to be of glass and outside glitters the host of heaven. Let us for a moment suppose that I were able, on December 21, to produce the Earth's axis from the North Pole indefinitely into Space. I should then arrive (at least approximately) at the Pole Star (which precisely for that reason is called so; it is star α of the Lesser Bear). The Pole of the Canopy of Heaven, the point where my indefinitely produced axis cuts the vault of heaven, that is, the point round which this vault performs apparent revolutions, is situated close to this star. Well, if on June 21 I produce the Earth's axis, I arrive at exactly the same point of the

[1] We shall even see (page 106) that the moon high in the heavens is slightly *larger* than near the horizon. The difference, however, is too small to be observed by means of a threepenny bit.

heavens. *The direction, therefore, has not changed;* the distance the Earth has travelled in its orbit is of no significance whatever in relation to Space. The Earth, at the end of half a year, performs its axial rotation *unchanged* in Space, unchanged, that is, in relation to the starry host, yet considerably changed with regard to the sun.

June 21

If on December 21 the North Pole was turned away from the sun, now, on June 21, it is turned to it. The result is that on Earth conditions are practically the image of those obtaining on December 21. The North Pole is basking in the sunshine, the South Pole is enveloped in darkness; the length of the night, at any point on Earth, is equal to the length of the day on December 21; at the Equator the sun is in the North at 12 o'clock, at $23\frac{1}{2}^\circ$ from the Zenith; on the Tropic of Cancer in the Zenith; in London not less than $61\frac{1}{2}^\circ$ above the Southern horizon. (*See* drawing of our model on June 21, Fig. 14.) So we see that on the Northern hemisphere winter has turned into summer, on the Southern hemisphere it is the other way about, while at the Equator little has changed.

September 22 and March 21

We give the Earth another quarter turn and are now in autumn, September 22. The Earth has now reached wall No. 4 in our model. The Earth's axis is still pointing in the same direction, the North Pole is still facing wall No. 1, but it is now neither turned to the sun nor away from it. The axis is perpendicular to the line connecting Earth and sun. And the consequences are clearly visible in our model. Both at the North and the South Pole the sun is on the horizon. At the North Pole it is about to set after the long Arctic day; at the South Pole the sun is rising after an equally long Antarctic night. On this date day and night are of equal length everywhere on Earth; at the Equator the sun is exactly in the Zenith at noon; both on the Northern and

the Southern hemisphere the meridian altitude of the sun, from Equator to Pole, decreases from 90° to 0°; on the entire Northern hemisphere the sun is in the South at noon, on the entire Southern hemisphere in the North. (Between the

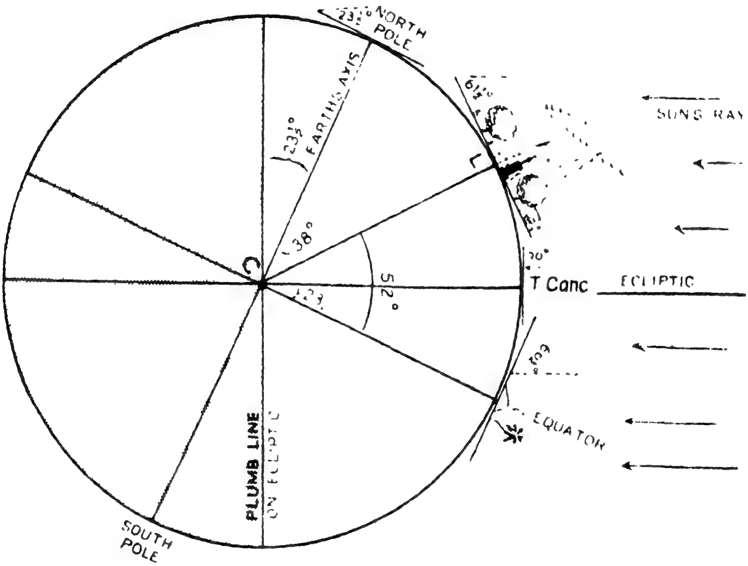


Fig. 14

THE EARTH ON JUNE 21, AT NOON (GREENWICH MEAN TIME). SUMMER ON THE …RN HEMISPHERE

L—London. T. Canc—Point on Tropic of Cancer. Since the 21st December the Earth has performed half a revolution round the sun, so that the sun is now "on the other side" and the sun's rays, in our drawing, come from the right. The direction of the Earth's axis has remained unchanged. But the North Pole is now turned towards the sun. The "drama of daylight life" is now enacted "facing the other side of space." In the number of full days that have elapsed since December 21, noon, the Earth has performed an equal number of rotations, plus one half rotation. Remember the difference between solar and a sidereal day. Observe that in London the day is now long and the night short, contrary to December 21. At the equator the sun is in the North. On the Tropic of Cancer the sun is in the Zenith. Sun's altitude: in London 61½°; at the equator 66½°; at the North Pole 23½°.

Tropics, hence in the tropical regions, this is not always the same in the course of the year, which will be clear from the preceding pages.) Conditions on March 21 (near wall 2) are a faithful copy of those obtaining on September 22, at any rate as far as the above-mentioned facts are concerned.

We already stated that on those two days the position

of the Earth strongly resembles that which it would take up if the axis were perpendicular to the ecliptic. We can now also understand *why;* at the equinoxes (March 21, September 22) the Earth's axis is neither turned towards the sun nor away from it, and although it is not perpendicular to the ecliptic (the angle of inclination never changes), it is at least perpendicular to the line connecting Earth and sun.

This, then, disposes of the whole mystery of the seasons; in our simple model we can see how everything happens. Call up in your mind a clear picture of the model, scan the drawings once more, and you will be satisfied that the whole complex of phenomena may be accounted for by the following causes: axial rotation, the Earth's revolution about the sun, and inclination of the Earth's axis. The difference in temperature between winter and summer now hardly needs elucidation; it is the direct outcome of the differences in length between night and day, and of the different altitudes of the sun above the horizon (discussed on page 69). The longer the sun shines the longer the relative portion of the Earth is heated; the longer the night, the stronger the effect of cooling. The coldest time of the year is shortly after the shortest day with the lowest altitude of the sun. On an average January 20 is the coldest day in our country, that is about four weeks after December 21. The hottest part of the year, in our country, is about mid-July. This is because for some time after June 21 the Earth continues to receive more heat than it gives off. (In the same way the hottest part of a day is not at twelve o'clock, but some hours later.) The reverse happens after December 21.

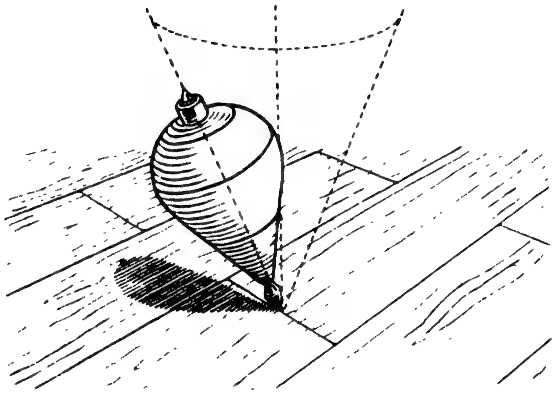
The Precession of the Equinoxes

Before taking leave of the seasons we must devote some lines to what is termed the precession of the equinoxes. This is no simple matter. And the worst part of it is that we must, so to speak, let go our hold on the unchangeability of the direction of the Earth's axis. It is not so serious as

it sounds, for we are here dealing with a movement taking a period of no less than 25,800 years for its completion. We have seen that the Earth's North Pole, which at first was straight above the floor of our room, could be lowered in any desired direction to the exact angle of inclination. Further, that there was a circle containing all possible "polar points," which circle corresponded with the northern polar circle of the Earth in its original position in our model. Well, the North Pole of our real Earth describes this circle clockwise in the above-mentioned period of 25,800 years. It would lead us too far here to give an explanation of this phenomenon. Let it be sufficient to state that it is consequent upon the Earth's being flattened at the Poles.

The angle of inclination is stationary at $66\frac{1}{2}°$, yet the Earth's axis, after 12,900 years, will point towards quite a different part of the universe. The celestial pole in the course of 25,800 years, describes a circle among the stars. Within a thousand years our Pole Star will have ceased to be Pole Star, not to become it again until after 25,000 years! In that period the picture of the heavens will undergo quite a considerable change. The pole describes $\frac{1}{25800}$ of that circle in one year, in a direction counter to that of the Earth round the sun. Suppose the circle in question were described in so short a period as twelve years. What would happen? In one year the pole would describe $\frac{1}{12}$ of the circle, so that after little more than 11 months, that is $\frac{11}{12}$ of its revolution round the sun, the Earth, *as regards the position of its axis*, would take up the same place in relation to the sun. We should then have to regulate our calendar year accordingly. Something more than eleven months would be the length of our civil year. For should we choose a different length, say, that of the Earth's revolution round the sun, our calendar would utterly fail to keep the seasons within fixed dates. And that, as we have seen, is the main purpose of the calendar. Fortunately, the precession of the equinoxes is a slow process; in one year only $\frac{1}{25800}$ of the circle is described. But fundamentally this makes no

difference. Just a little before the Earth has completed a revolution about the sun, it will have reached the same point in its orbit as regards the seasons. In other words, the year, on which our calendar of the seasons is based, is shorter than the *real* year, defined by a complete revolution of the Earth round the sun. The difference is slightly more than 20 minutes ($\frac{1}{25800}$ of a year). The *tropical year*, which forms the basis of our calendar year, is 365 days 5 hours 48 minutes 46 seconds; the *sidereal year* is



In 25,800 years the North Pole of the Earth describes the indicated circle. The comparison with a top makes it clear that the angle of inclination remains unchanged.

365 days 6 hours 9 minutes 11 seconds, the latter year being equal to the duration of one revolution of the Earth round the sun. In 25,800 of our years the Earth will have performed a number of revolutions round the sun, which is one less than the number of seasonal years.

The summer solstice and the winter solstice do not, therefore, occur at fixed places in the Earth's orbit. They move along the whole orbit in 25,800 years. After 12,900 years our descendants on the Northern hemisphere will have summer in that part of the Earth's orbit where it is now enjoyed by their Southern brethren. In our model it will

then be summer on the Northern hemisphere near wall No. 1. For the Earth's axis will then have made a half turn.

Other Influences affecting the Seasons

It should further be remarked that the Earth's orbit round the sun is not a circle, but an ellipse. That means that in the course of the year the distance between the Earth and the sun is not constant. The difference between the greatest and smallest distance is, relatively speaking, small, being slightly over 3 per cent. The point closest to the sun (perihelion) is reached by the Earth on January 2, hence in the middle of the winter on the Northern hemisphere; the point furthest from the sun (aphelion) is reached half a year later. Although 3 per cent. is not much, yet it affects the quantity of heat which the Earth receives from the sun. The consequence is that on the Northern hemisphere both summer and winter are a little more temperate (the summer somewhat cooler, the winter somewhat milder) than would otherwise be the case. On the Southern hemisphere the reverse obtains: the summer is somewhat hotter, the winter somewhat colder.

Finally we would point out, for completeness's sake, that the perihelion and aphelion, too, slowly move along the Earth's orbit and make a complete round in tens of thousands of years. We have just seen that the seasons travel along the Earth's orbit in 25,800 years. So here are two very slow processes at work. A third is provided by the fact that in the course of thousands of years the difference between the greatest and the smallest distance from the Earth to the sun alternately decreases and increases, while in the fourth place the angle of inclination of the Earth's axis first decreases to 21° 59′ and then again increases to 24° 36′, the process occupying a very long period of time. All these movements, either directly or indirectly, affect the seasons. For thousands or tens of thousands of years these influences may neutralize one another entirely or partly; in other periods they may all or practically all work in the same direction. Thus the winter half of the year, which at present in the Northern hemisphere is 7 days shorter than the summer half, may become 33 days longer than the latter. It is therefore possible for those factors to change the climate quite considerably in the course of tens of thousands of years. But it is doubtful whether they are of sufficient importance to account for the various ice-ages in the past. On the other hand it is an established fact (quite contrary to popular opinion) that down from the remotest historical times the climate in our regions has undergone no material changes. The so-called "old-fashioned" winters are nothing but products of the imagination.

The Aspect of the Heavens at various Periods of the Year

We have dwelt quite long enough on the seasons and are now going to devote some lines to the changing aspect of the visible universe during the various parts of the year. The problem is to a certain extent linked up with the preceding one. We all know that the aspect of the heavens changes from night to night. Every night the same star passes the meridian (that is the line running from North to South through the Zenith) four minutes earlier. This gives a difference of two hours in one month.

On February 1, at 8 o'clock in the evening, the heavens present the same aspect as on January 1 at 10 p.m. The reason for this was given on page 47: it is the difference *between a sidereal and a solar day. We shall now look at the matter more closely.*

The same model that served for the seasons may give excellent help and, as you will presently see, the problem is by no means so difficult as that of the seasons.

We place the Earth in its natural position near wall No. 1. We again affix our plane of the horizon to the North Pole and set the Earth rotating round its axis, nothing else. We switch off the sun and instantly, through the glass walls, the glass roof and the glass floor, we see the stars of heaven flash into prominence. But which of these stars are visible from the North Pole? The answer is readily given. We need but extend the plane of the horizon in every direction. Standing at the North Pole we can only see the stars above that plane, for we cannot see round the horizon or through the Earth. While the Earth rotates round its axis this plane remains unchanged. On the supposition that one part of the Universe contains as many stars as another, we may say that we can only see one-half of all the stars. At the North Pole the Pole Star is now—and will be for another thousand years—in, or rather near, the Zenith. All other stars, to our eye, describe larger or smaller circles round the Pole Star, parallel to the horizon. The higher

they are in the sky, the smaller the circle. Not a single star rises, or sets. They revolve in 23 hours 56 minutes 4 seconds, day after day. One-half of the Universe is continually visible, the other half never. The Arctic night lasts half a year and for half a year we can watch the circling movement of the stars. Then comes the Arctic day, and although the stars continue their circular course, we cannot see any one of them with the naked eye.

We need scarcely point out that at daybreak the stars do not really disappear, but only become invisible to the naked eye owing to the fierce sunlight. Through a telescope, and even through a long narrow tube, we can see the stars also in the daytime, at least the brightest ones, while during a total solar eclipse the stars become visible to the naked eye in the middle of the day. But we are anticipating. *Our Earth is still rotating round its axis near wall No. 1 and the sun is off. You wonder what picture the heavens will present to inhabitants in other parts* of the Earth? Just come with me to the Equator, to Pontianak. Here, too, we affix our plane of the horizon, which now runs parallel to the Earth's axis. We notice that, whereas at the North Pole our plane of the horizon underwent no change while the Earth rotated, at Pontianak it revolves with the Earth, continually facing a different part of the Universe. Since, in comparison to distances in space, the Earth's dimensions are of no significance whatever, the inhabitants of Pontianak will successively see all parts of the Universe, hence all the stars, in the course of one rotation. All stars, to them, rise at the Eastern horizon, and set in the West 11 hours 58 minutes later. A star which rises due East will traverse the sky through the Zenith, and set again due West. The arc which a star traverses will be smaller according as it is seen more to the North or to the South. Stars that are always visible at the equator do not exist, nor those that are never visible there. At the Pole one-half of the stars is always visible, the other half never; stars

that rise and set are not to be found there at all. You will realize the sharp contrast between Poles and Equator in these matters (*see also* Fig. 15). At other latitudes things are not so simple. On travelling northward or southward from Pontianak the aspect of the heavens must be gradually metamorphosed to that of the Poles. For our examination we choose a point about half-way between Pontianak and the North Pole, say, London in about Latitude 52° N. If we now pin our plane of the horizon on to London and set the Earth rotating round its axis, we soon notice that the stars, as regards their visibility from London, may be divided into three groups, notably, one group which never sets, hence is always visible above the horizon, a second group which rises and sets, so is visible for a certain time in every 24 hours, and a third group which is never visible (*see* Fig. 15). The part of the Universe which is always visible from London is as large as that which is never seen. The Pole Star is seen due North at 52° above the horizon (as many degrees as is the latitude of London[1]) in a well nigh fixed position. The stars in the vicinity of the Pole Star describe small circles round it in 23 hours 56 minutes and, consequently, are always visible. The further a star is from the Pole Star, the greater the circle it describes, but all stars which, in the vault of heaven, are less than 52° from the Pole Star, do not set in London. More than a quarter of the Universe is always visible from London and—as we observed above —an equal part is always hidden from our view. A star that is at more than 52° from the Pole Star must disappear behind the horizon for a certain period, the longer as its distance from the Pole Star in degrees of arc is greater. At still greater distances from the Pole Star there will be stars which merely pop their heads above the Southern horizon, while finally come the stars which never rise above the

[1] This, as the reader will readily see, is no mere chance. Everywhere on the Northern hemisphere the Pole Star is a wellnigh fixed point in the North, at *exactly so many degrees above the horizon of a given place as is indicated by the latitude of that place.* A careful scrutiny of Fig. 15 will make this perfectly clear to anybody, while those who have learned geometry will be able to prove it in no time.

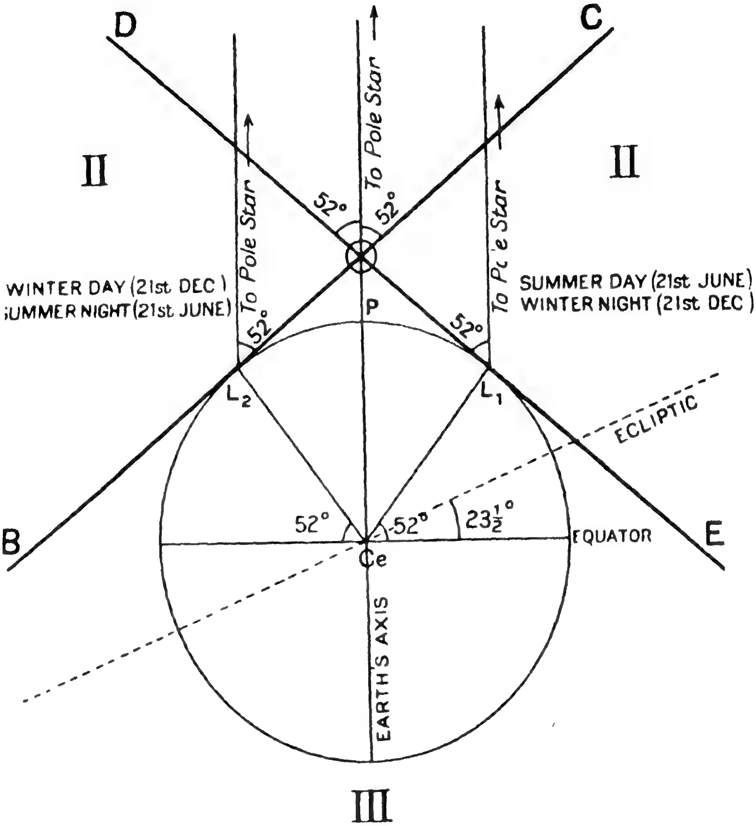


Fig. 15.

ASPECT OF THE HEAVENS IN LONDON IN THE COURSE OF THE YEAR.

figure the Earth's axis has a perpendicular position, so that the ecliptic must This way of representing things is, of course, quite permissible and in this case even preferable, because it is clearer.

Ce—Centre of the Earth.

P—North Pole.

L_1—London on June 21, noon, and on December 21, midnight.

L_2—London on June 21, midnight, and on December 21, noon.

At midnight on December 21 all stars are visible which are to the right of line DE, on June 21 all stars to the left of line BC. The stars within angle DOC (group I) are therefore always visible, those within angle BOE (group III) never. Those enclosed by the angles BOD and COE (group II) rise and set. At midnight on June 21 exactly the opposite half of the stars of this last group is visible as on December 21 at midnight. The Pole Star being, relatively speaking, at infinite distance, the lines indicating its direction may be taken as running parallel.

London horizon. We must then travel further and further south to see more stars of the Southern hemisphere.

What applies to London is equally true for any other place between the Equator and a Pole, with this difference, that towards the Poles, hence at greater latitudes, the number of stars of the first group (the ones that never set) and those of the third group (which are never visible) continually increases. North of us that number is larger, South of us smaller. The part of the Universe that is always visible is, in any part of the world, as large as the part that is never visible. The number of stars of the second group (which rise and set) decreases from the Equator (all stars) to the Pole (none). The total number of stars visible in twenty-four hours also decreases from the Equator (the whole Universe) to the Pole (half of the Universe).

We have now acquired a fairly accurate idea of the visibility of the stars from different parts of the Earth while it rotates round its axis. We now set the rotating Earth travelling round the sun, but keep the latter dark. And we are anxious to see what difference it makes to the different parts of the Earth. None at all! The Earth's axis remains —at any rate in a lifetime—directed towards the same point of the heavens, so that the axial rotation, in relation to the stars, is effected in exactly the same way throughout the Earth's revolution round the sun. So long as the axis retains its position, the Earth's movement about the sun is immaterial so far as the stars are concerned, barring of course aberration and parallax, which we may ignore because they are undiscoverable to the naked eye or even to small telescopes. So long as the direction of the Earth's axis remains unchanged, the aspect the heavens present to some point of the Earth's surface during one rotation (if we keep the sun out of it) will remain equally unchanged. Every 23 hours 56 minutes 4 seconds the same picture of the stars is enjoyed at a given point on the Earth's surface.

But we now switch on the sun, while the Earth is kept rotating and revolving round the sun. And at once a

complete change is noticed as regards the visibility of the stars (to the naked eye). With the sun on we transfer the Earth from wall No. 1 to wall No. 3. The effect of this movement on the North Pole has practically been discussed already; at the Pole not a single star is seen any more, from Arctic night it has become Arctic day. But what happens at the Equator, at Pontianak? What is the difference between the situation near wall No. 1 and that near wall No. 3, or, in other words, between December 21 and June 21?

As soon as we put out the sun the difference is nil. But when the sun is on, the difference is as large as possible: midnight at Pontianak, on June 21, occurs facing the opposite side of the Universe to December 21. This means that at midnight on June 21 people at Pontianak see one-half of the stars and at midnight on December 21 exactly the other half. Not a single star is visible at Pontianak at midnight on both dates.

Our model again makes the situation in London perfectly clear to us. At midnight on December 21 London faces partly the same, partly a different portion of the Universe as on June 21. Part of the stars visible in London at midnight on June 21 and December 21 are the same; it will be clear that they are those stars which never set in London. But of the stars of the second group (which rise and set in London) not a single one will be visible on *both* dates at midnight. Of these stars London, at each of the points of time mentioned, will see exactly "the other half." (*See* Fig. 15.)

We are now sufficiently acquainted with the Earth, its chief movements and all phenomena consequent upon them. Our next step will be to leave the Earth and start on our journey into Space. Our first visit will be to our nearest neighbour, the moon.

CHAPTER II

THE MOON

Distance of the Moon

WE pointed out in the first pages of this book how all phenomena related to the *weather* occur in close proximity to the Earth's surface. The majority of the clouds we see floating in the air are not higher than 7,000 to 9,000 feet, frequently even lower than that; the highest cirrus clouds, those tiny feathery clouds, which are sometimes seen to drift across the blue canopy of heaven, are never higher than 35,000 feet. We have seen how small its altitude is relative to the Earth's dimensions; on our model of the Earth, a globe with a diameter of about 5 feet, the height is not more than 1 millimetre ($\frac{1}{25}$ of an inch). Hence, even if we have reached those highest clouds we have by no means left the Earth yet.

But things become different if we set out on a journey to the moon. The moon is at an average distance of 239,000 (two hundred and thirty-nine thousand) miles from the Earth. That is a hundred thousand times as far as a rather high cloud, and yet it is not so very far. No more than thirty terrestrial globes might be pushed in between the Earth and the moon; taking our model as a basis, the moon would have to be at about 150 feet from the Earth. The distance to the moon still allows of comparison to ordinary earthly distances: the differences are not disproportionate. The distance between two antipodal points on Earth (measured along the Earth's surface) is 12,500 miles. The moon is 19 times that distance away from us. If we were able to traverse the distance of 239,000 miles separating us from the moon, by aeroplane in a straight line at the rate of about 125 miles per hour, we could complete our journey

in 80 days, that is, the same time as it took Phileas Fogg to travel round the world.

Relatively speaking, therefore, the moon is fairly near to us; we shall presently see that in terms of astronomy it is very close indeed, and that it is not only our neighbour, but our child as well.

How do we determine the distance to the Moon?

The first question that arises is how to determine the distance to the moon. The fact that this heavenly body is, relatively, so near makes the determination easy, easier than for any other heavenly body. The procedure is as follows: Take two points on Earth at a distance of 10,000 kilometres (6,215 miles) one from the other (measured—or rather, calculated—through the Earth). If these points are chosen with care the moon may, for a certain time, be observed from both places simultaneously (*see* Fig. 16). The place occupied by the centre M of the lunar disc is now determined as accurately as possible from the points A and B at the same moment, for instance at the moment when the moon is straight over the middle of line AB. One then knows how many degrees, minutes and seconds that centre is at that moment above the horizon, both in A and B, or, in other words, one has measured the shaded angles MAH1 and MBH2. There is now no difficulty in calculating, in triangle ABM, the angles adjacent to the base AB. The vertical angle M will then be 180° less the sum of the other two angles, since in any triangle the three interior angles are together equal to 180°. If the measurements have been carried out accurately, the two angles at the base AB prove to be 89° 16′ each; this leaves 1° 28′ for the vertical angle. Now, by means of trigonometry, all sides of a triangle of which one side and the angles are known, may be calculated. But here we shall apply a simpler method. If the vertical angle be 1° 28′, this means that the distance of 6,215 miles in a straight line on Earth presents an angle of 1° 28′ when viewed from the moon. Now, in any circle there is a fixed relation between circumference and radius. The proportion is about as 44 to 7. Hence, a quarter of the circumference is to the radius as 11 : 7, an arc of 45° as 11 : 14, an arc of 4° about as 1 : 14, an arc of 1° about as 1 : 57. Consequently, if an object with a diameter of 35 feet, say, a balloon, is so far away from us that it presents to the eye a diameter of 1° of arc, that balloon will be at a distance of 57 × 35 feet or 1,995 *feet*. If the size of the balloon, as it recedes in the distance, has decreased to the apparent diameter of the sun (about ½° of arc) the balloon will be about 3,990 feet away from us. In the

same way we find for 1′ a multiplication factor of 3,438. Suppose we were able to see our balloon through a telescope when in the sky it presents a diameter of 1′ of arc, we should then know that it was at that moment 3,438 × 35 feet or about 22·7 miles away from us.

We found 1° 28′ for the angle at which our distance of 6,215 miles was seen from the moon. As we saw just now, 1° corresponds to a ratio of 57 to 1; hence 1½° (1° 30′) corresponds to a ratio of 38 to 1. The angle found is slightly less, hence the distance will be somewhat greater, say, ratio about 38·5 to 1. It follows that, if a distance on Earth of 6,215 miles presents an angle of 1° 28′ when viewed from the moon, *the distance from the moon to the Earth must be about* 38·5 × 6,215 *miles, or about* 239,000 *miles.*

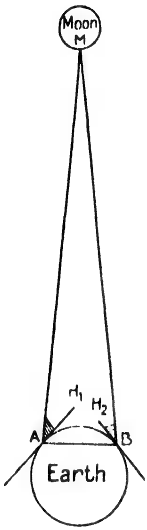


Fig. 16

Determining the distance to the moon

This method cannot be employed for remote heavenly bodies, the vertical angle of the triangle then being too small. In the case of stars the distance of 6,215 miles between the observers is of no significance; the direction in which they see a certain star is practically the same: the lines to that star run sensibly parallel; hence the vertical angle is too small to measure with our instruments. When dealing with parallax we mentioned that the diameter of the Earth's orbit round the sun, about 186,000,000 miles, is scarcely sufficient to provide a base for the triangle, even where the nearest stars are concerned.

Size of the Moon

As soon as we have determined the distance from the Earth to the moon, it is quite simple to calculate the size of the moon. We know the diameter it presents to our eye (about half a degree) and its distance; from this we can calculate the size. According to what we reasoned out above, the moon, should it present a diameter of 1° to our eye, would have a real diameter of $\frac{1}{57}$ of its distance from us. But the apparent diameter is slightly over ½°, so that we must divide not by 57, but by 111. This yields for the diameter of the moon about 2,160 miles, or rather more than ¼ of the Earth's diameter.

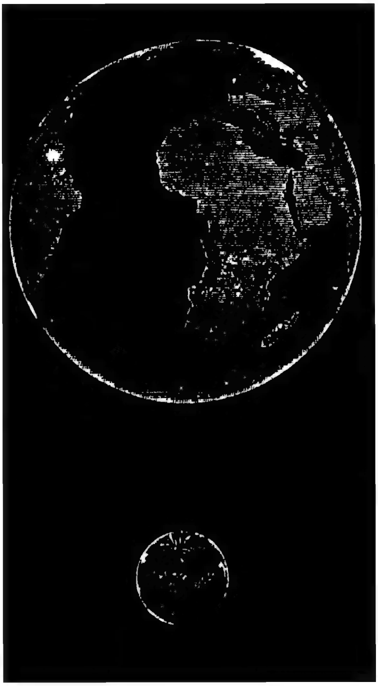
The moon, therefore, is quite an unpretentious little globe

compared to the Earth, and still more so than one would conclude at first sight from this proportion of 4 : 1. For do you all fully realize how this affects the solid capacity? With spheres it is the same as with cubes. If we compare two cubes, one with an edge of 1 inch and another with an edge of 2 inches, we all know that the solid capacity of the latter cube is $2 \times 2 \times 2$ or 8 *times* as large as that of the former. If the edge is not twice but three times as large, we find the proportion to be $3 \times 3 \times 3 = 27 : 1$. With 4 we find, obviously, 64; with 5, 125; with 10, 1,000, and so on. Now it is the same with spheres. If the diameter of a sphere is four times that of another sphere, the proportion in size will be as 64 : 1. For the solid capacity of a sphere $\frac{4}{3} \pi r^3$, that is $\frac{4}{3} \times \pi \times$ radius $\times$ radius $\times$ radius. π is the famous factor indicating the relation between the circumference and diameter of a circle. It is about $\frac{22}{7}$ (more accurately 3·14159265358979. . . .).

If the Earth's diameter were exactly four times that of the moon the Earth would be exactly 64 times the size of the moon. It is, however, slightly less than four times as large, and the true relation between the volumes of the Earth and the moon is about as 50 : 1.

The moon, then, is only an insignificant little globe by the side of the Earth. We can convince ourselves of this by taking a model globe with a diameter of 4 inches to represent the Earth, hence an Earth the size of a fairly large orange. By the side of it the moon will be a small globe 1 inch in diameter, hence not larger than a marble. If we want to place this marble at the right distance from the Earth, we shall have to leave an open space of, roughly, 30 times the Earth's diameter, i.e. about 10 feet. We may at once add that the moon will then, when viewed from the Earth, present an angle of about half a degree, quite in keeping with reality. We shall see, later on, that on the scale of our model we shall have to go hundreds of yards to reach another celestial body, a nearby planet or the sun, to say nothing of the stars that are at immeasurably great distances. This already gives you

an idea of what a solitary body our Earth is in space. But in our model, where about our Earth of 4 inches diameter nothing, absolutely nothing, is to be found for hundreds of



RELATIVE SIZES OF THE EARTH AND THE MOON

In proportion to the sizes in this picture, the distance between Earth and Moon would be a little over a yard and a half.

miles, our small marble is floating at a distance of not more than 10 feet. If I place my Earth in one corner of the room there is still space enough left in it for my moon to

be placed at the proper distance. But outside, on the entire square in front of my house, there is nothing but emptiness, devoid of any heavenly body whatsoever. So it is well to say that the moon belongs to the Earth, that it is the Earth's companion, its child. And, as we shall see later, the moon was born of the Earth. It never leaves Mother Earth and does not tire of performing its monthly round about her.

Why does not the Moon fall?

Why does not our small marble move towards the Earth? Why does not the moon fall to the Earth? We are, all of us, by now familiar with the fact that, speaking in terms of space, there is no above or below. So long as we spoke about the Earth alone, there was hardly sense in asking why the Earth did not fall. For, given one heavenly body in the whole Universe, whither should it fall? It might "move" in any direction, and we have even seen that in the case of one single body in the Universe it is impossible to speak of rest and movement.

But this explanation does not dispose of our question if, as in our case, we have to do with *two* heavenly bodies. Why does not the moon, that tiny globe, fall to the Earth, which is so much larger? Or, to be more accurate, why does not the attractive force of the Earth, namely that attractive force exercised by the Earth which causes terrestrial objects to fall towards the centre of the Earth, which we call the Earth's gravity, cause the moon to move towards the Earth, at first slowly, but with gradually increasing speed, until it crashes down upon the Earth with a terrific impact and is shattered to pieces?

And we are surprised that, in spite of this force of gravity, the moon does not fall. How is that? The answer must be that, properly speaking, it *does* fall.

Isaac Newton

We shall try to explain this. On a fine summer evening in the year 1666, a young man aged twenty-three was sitting

under a tree. It was Isaac Newton, afterwards to be such a famous scientist—Isaac Newton, whose memory will live as long as there is a human soul on Earth and whose name will always be pronounced with reverence.

Newton is the father of the theory of universal attraction *of matter. But in 1666 he was still a young man dreaming under a tree. Through the foliage the moon was shining. The tree was an apple-tree and suddenly an apple hanging "close to the moon" dropped to the ground. And Newton* thought: "Why does that apple fall, and why does not the moon fall?" Why has the moon kept revolving about the Earth in $27\frac{1}{3}$ days all through the ages without falling towards the Earth? Or is it that the moon really *does* fall to the Earth? Is the almost circular orbit of the moon round the Earth perhaps the resultant of two movements, the moon's own movement and another earthward movement, a fall caused by the gravitational pull of the Earth?

Newton began to study this matter more closely. There was ample reason for it, too. A stone thrown in a horizontal direction will fall to the Earth at a few yards' distance. The gravitational pull of the Earth (commonly called gravity) has dragged that stone gradually down. If we follow the trajectory of that stone closely with our eyes, and then make a drawing of it, we shall see that we have obtained a kind of long-drawn-out curve, the combined result of the stone's own movement and the attractive force of the Earth. This curve, it is true, is far from being part of the circumference of a circle, but still it helps us to understand that under certain conditions a circular movement might be the combined result of a body's own movement and the gravitational force of the Earth.

To make his calculations Newton had to know the exact distance from the moon to the Earth and, by deduction, the extent of its orbit. Unfortunately, in the year 1666 these data were not yet known accurately. Newton then still thought that the moon was at a distance of only 200,000 miles, instead of 239,000 miles, from the Earth. This grave error

upset his calculations and a disappointed Newton thought he had to confess himself wrong in his conjectures.

Sixteen years later, in 1682, he happened to learn the result of a new calculation of the Earth's dimensions, when it appeared that the Earth's diameter was considerably larger than the 6,800 miles people had assumed it to be until then. It had been known for quite a long time that the moon was at a distance of 30 Earth-diameters from the Earth, but because he had taken this diameter to be 6,800 miles only, his estimation of the distance to the moon had been wrong. It now appeared to be 239,000 miles.

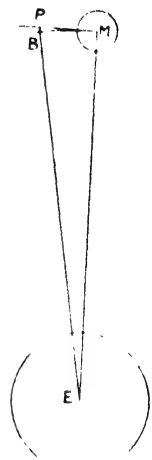


Fig. 17.

The Movement of the Moon explained

Armed with these new data, he now repeated his calculations and everything tallied admirably.

In order to understand these calculations, refer to Fig. 17, where E is the Earth, M the moon. The supposition is, as we have seen, that the circular orbit of the moon—of which MB is a small part—is caused by the moon's own movement and a fall to the Earth occasioned by the gravitational pull of the latter. Now we assume that the moon has a movement of its own in the direction MP and that in one second it travels from M to B. (It must be understood that this arc has been exaggerated in the figure, but for clearness's sake this is unavoidable.) What we try to imagine is whether the fact that in one second the moon has travelled from M to B along part of the circumference of a circle, can be accounted for by assuming that without a fall it would in that second have travelled along the straight line MP in a direction at right angles to ME, but that at the same time it has fallen from P to B, that is towards the Earth. Its movement is then analogous to that of the stone I threw away in a horizontal direction at a height of one yard. By the force of my throw alone it would, in the same time, have arrived at a point one yard above the spot where it has now come down. But it has at the same time dropped one yard owing to the attractive force of the Earth (gravitation) and has consequently struck the Earth.

We know that the distance EM (from centre to centre) is about 239,000 miles. EB = EM, hence also 239,000 miles. MB is the distance the moon has travelled in one second. How long is that distance? The moon completes its orbit round the Earth in $27\frac{1}{3}$ days; the moon's orbit is 1,491,000 miles in circumference. From this it follows that the moon moves at the rate of 1,130 yards a second. (This calculation is very simple: 1,491,000 miles is divided by 2,360,000, the number of seconds contained in $27\frac{1}{3}$ days, and the quotient converted to yards.) We have now to calculate the distance from P to B, that is the distance the moon has "fallen" in one second. Since ME, BE and BM are known and EMP is a right angle, it is possible, by means of elementary geometry, to calculate the distance PB.[1]

This proves to be slightly more than $1\frac{1}{3}$ millimetres or more accurately 1·36 millimetres (one millimetre is about $\frac{1}{25}$ inch). Hence, if Newton's conjecture is correct, the moon, as a result of the gravitational pull of the Earth, falls towards the Earth 1·36 mm. in one second. Now, a stone on Earth by gravity, in a vacuum, falls 16 feet (4,900 millimetres) in the first second of its fall. (In the ordinary atmosphere this velocity is somewhat less owing to resistance of the air.) Newton was able to show that gravitation at the surface of the Earth and beyond, works as if the seat of that force were in the centre of the Earth. All falling objects, therefore, tend towards the Earth's centre. From the above it follows that at the Earth's surface the force of gravity works at a distance of about 4,000 miles; on the moon at about 60 times that distance. Now it is quite natural to suppose that the attractive force weakens as we recede from the Earth, and Newton assumed that the force of gravity fell off inversely as the square of the distance. This means that at twice the distance from the centre to the surface of the Earth the gravitational pull must have become 2×2 or 4 times as small, or, in other words, must have weakened to $\frac{1}{4}$; at three times the distance to $\frac{1}{9}$, at four times the distance to $\frac{1}{16}$, at 60 times the distance to $\frac{1}{3600}$. Therefore, if the moon falls towards the Earth, it must fall $\frac{1}{3600}$ times as slowly as it would do at some yards distance from the Earth, in the first second. Now, we have seen that a stone near the Earth's surface falls 16 feet (4,900 mm.) earthwards in the first second. Divide this by 3,600 and you will find exactly 1·36 millimetres. And thus the moon travels on in the same way; in B it is in a similar position to M. By its own movement it tends to voyage into space along the tangent to the circle in point B, but is "drawn down" by the gravitational pull of the Earth. In the next second, being still at the same distance from the Earth,

[1] Approximate formula: PM is to BM as BM is to the diameter of the moon's orbit.

the moon again drops 1·36 mm. earthwards and thus describes its circular course as the combined result of its own movement and its earthward fall. Accordingly Newton deduced that the force which keeps the moon in its orbit is the same force which attracts terrestrial bodies at the surface of the Earth and makes them fall.

The reader will probably still have one objection to offer that needs discussion. It will be clear to him that if a stone on Earth falls 16 feet (4,900 millimetres) in the first second, the same stone at 60 times the distance from the Earth centre, that is where the moon is, will fall with a velocity of 4,900 millimetres divided by 3,600 = 1·36 mm. in the first second. But, he will argue, what about the moon itself, which, compared to the stone, has such an immense size: will it not fall faster?

This argument is not difficult to refute, since *on the surface of the Earth, a big stone falls with exactly the same velocity as a small one, at least in a vacuum.* In a vacuum a big stone, a small stone, a grain of sand, and even a bit of cork or a feather, fall at the same rate. Many of our readers will have seen this interesting experiment made in a glass tube from which the air has been exhausted by an air-pump. That things are different if a stone and a cork, or, better still, a feather, are thrown from a tower, is merely a question of resistance of the air. Relatively speaking, a small stone meets with greater resistance from the air than a big one. Hence a big stone falls at a somewhat more rapid rate than a small one. And this phenomenon leads us to believe that the gravitational pull makes a big object travel faster than a small one, so much the more when we compare a stone with the moon. "But," the reader will ask, "is the effect of the attractive force of the Earth on the moon and on a stone at an equal distance, the same? Given the same distance, is the attractive pull of the Earth on the stone equal to that on a heavenly body a million times the mass of that stone?"[1]

[1] The term mass, here used for the first time, may be conceived by the reader as being equivalent to quantity of matter. "Mass" and "weight" should not be confused, for, whereas any body has the same mass everywhere, its weight may vary widely at different places as we saw on page 33.

By no means! In the latter case the attractive pull is exactly a million times as great. This need not surprise the reader, if in thought he divides the heavenly body into a million stones each with a mass of one. But he must not forget that to give to an object a million times that mass the same rate of fall, to pull that object towards the Earth with the same velocity, a force a million times as strong is required. That is why a stone, nay, even a grain of sand, at the distance of the moon, falls to the Earth at exactly the same rate as the moon itself. And even a feather is no exception, for in space there is absolute vacuum.

Universal Gravitation

Newton's amazing discovery, then, was that at one stroke he was able to account for all movements of all heavenly bodies by one simple fundamental law. Besides, all those movements could now also be calculated and predicted for eternity. For, if the moon's motion round the Earth is caused by gravitation, the movements of the Earth and the other planets round the sun are brought about by the gravitational pull of the sun; the movements of stars are consequent upon their mutual attraction. Gravitation is a universal property of all matter. And it invariably appears that all those movements in space can be explained, calculated and predicted by means of Newton's simple fundamental law: *All heavenly bodies, all objects, all particles of matter of which everything is built up, attract one another. Any two particles of matter attract one another with a force varying directly as the product of their masses and inversely as the square of their distances apart.* Newton's fundamental law afforded quite a simple explanation of three famous laws (to which we shall revert later) which *Kepler* had formulated not long before, in regard to the movements of the planets round the sun. All laws of motion operating in the Universe were reduced to one simple law of wide generality. Never has any discovery offered such a fertile basis for the further development of science. It is sometimes maintained that Newton's

theories have been "refuted" by Einstein's, but this is far from the truth. The general theory of relativity, Einstein's ingenious conception, should rather be looked upon as complementary to Newton's work. Einstein's splendid achievement does not in any way detract from the greatness of Newton's work.

We must say a few more words about Newton's law. We already observed that the Earth attracts the moon, thus causing it to turn about her, and that the sun attracts the Earth and the other planets. But this statement is not quite true. We ought to have said, the Earth and the moon attract *one another*, just as there is *mutual* attraction between the Earth and the sun. This follows directly from Newton's law. Any particle of matter attracts any other particle of matter. This at once leads to the amazing conclusion that the attractive pull of a single particle of matter on an immense bundle of particles, like the Earth for instance, is of the same strength as the Earth's pull on that single particle!

This seems incredible on the face of it, and yet it is so. The stone which I hold in my hand attracts the Earth with the same force as the Earth does that stone. Therefore, if I let go of the stone, it will fall to the Earth, but the Earth will also tend towards the stone. Both will be acted upon by equal forces. But since the Earth has at least a quadrillion times the mass of the stone, the Earth, under the pull of a force that makes the stone drop earthwards over a distance of one yard, will only move one quadrillionth part of a yard towards the stone, that is, practically, not at all. And that is why, in giving a simplified explanation of the effect of gravitation between the moon and the Earth or between the Earth and the sun, we may safely say that the moon falls towards the Earth (or the Earth to the sun) and not conversely, the latter movement being so exceedingly small that we need not trouble about it for our present purpose. Should we desire to be exact, we ought to say that both moon and Earth move about their "common centre of gravity," which does not lie in the centre of the Earth, but is situated slightly

in the direction of the moon, though within the Earth's circumference. Thus it appears that actually the Earth falls just a little towards the moon. But anyone who thinks this too involved may forget it. Only he must not suppose that astronomers may do so. When the positions of the Earth and the moon are calculated the moon's pull upon the Earth must be accurately taken into account.

In the nineteenth century people succeeded in demonstrating the general force of gravity by which ordinary objects on Earth must attract one another according to Newton's law. Very delicate and sensitive instruments are required for this. Delicate balances were even constructed by which the presence of gravitational pull could be definitely shown. To this end a weight of 2 lb. is put in both scales, while a heavy metal sphere of say 200 lb., is alternately placed *under* each of the scales. The balance then proves to dip on the side of the metal sphere. The attractive force of the sphere has pulled scale and weight down, and this can be ascertained by an increase in weight. You need not be afraid, however, that any shopkeeper will be able to cheat you in that way: even if a sphere of 200 lb. is placed as close as possible under one scale (the centre of the sphere can hardly be got nearer to the scale than 6 inches), the weight of 2 lb. on the scale will not increase in weight by more than $\frac{1}{30}$ milligram. The general force of gravity is a very weak force indeed.

But it is high time we got back to the moon. We have seen why the moon does not fall towards the Earth; how, in reality, it *does* fall and by combining this very fall with its own movement, it circles round the Earth. It is a continuous never changing movement, because there is nothing —no friction, no resistance of any kind, not even by molecules of air—in the vacuum of space to retard, arrest or otherwise counteract it.

The Motion of the Moon

The moon revolves about the Earth in $27\frac{1}{3}$ days, or, accurately, in 27 days, 7 hours, 43 minutes, 11·5

seconds. Let us examine this movement somewhat more closely.

To go into all movements governing the place of the moon in the Universe would be far beyond the scope of this book. For, if astronomers wish to calculate beforehand the position of the moon at a given moment with complete accuracy, they must take some hundreds of movements into account. But for our purpose it will suffice to find the *approximate* position of the moon in the heavens, and a description of some simple movements will make things perfectly clear.

At the same time as the moon, then, turns anti-clockwise about the Earth in $27\frac{1}{3}$ days, the Earth revolves about the sun and, in the course of one lunar revolution, the Earth has covered almost $\frac{1}{13}$ of its own yearly orbit round the sun. The reader will at once see that here a similar phenomenon occurs as that discussed on page 48 in connection with the difference between solar and sidereal days (*see* Fig. 18). Starting from the moment when the moon is exactly between the Earth and the sun, it is easy to see that after the moon has completed one revolution round the Earth, it will not nearly have reached the same position in regard to the sun. What will be the case is that, after one complete revolution of the moon, a line drawn from the Earth to the moon will have the same direction in space, hence will point towards the same star. For this reason this revolution of the moon is called "sidereal" revolution. But the sun, owing to the Earth having travelled to the right, is still well to the left, so that the moon, if it is to resume its position in the direction of the sun, must turn on for almost $2\frac{1}{4}$ days, or accurately, for 2 days, 5 hours, 0 minutes, 51·3 seconds. It follows that a revolution of the moon round the Earth until it has regained its previous position in regard to the sun, takes 29 days, 12 hours, 44 minutes, 2·8 seconds. This is the "synodic" revolution. We shall presently see that this is the time elapsing between two successive new moons (hence also between two successive full moons). It will be understood that this synodic month

is a mean value, and that it may be slightly longer or shorter, according as the Earth and the moon travel more swiftly or more slowly in their orbits.

The Moon's Orbit round the Earth

On accurate examination it is found that the moon's orbit round the Earth is not a pure circle, but an ellipse.

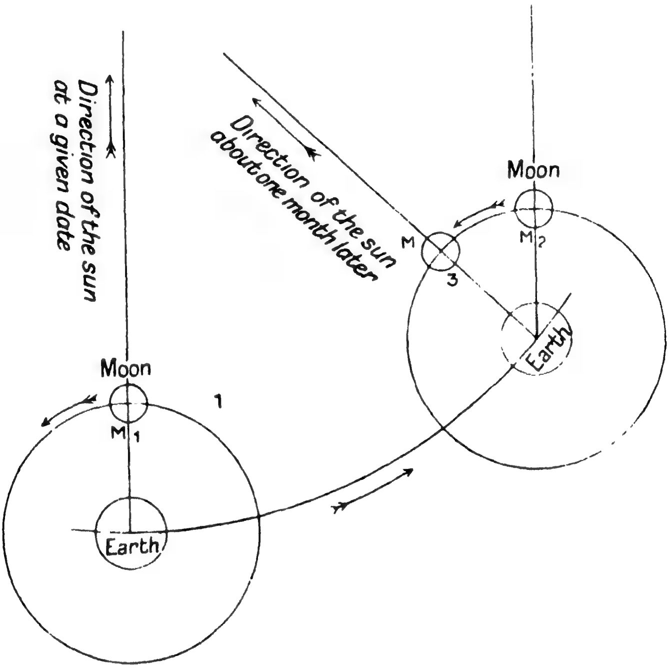


Fig. 18.

DIFFERENCE BETWEEN *Sidereal* AND *Synodic* MONTH.

In M_2 the moon has completed a full revolution round the Earth (sidereal month). It must then still travel to M^3 to resume its previous position in regard to the sun (synodic month).

That means that the distance between the Earth and the moon is not constant during the moon's revolution, the deviation from the circle being greater than in the case of the Earth's orbit round the sun. When the moon in its orbit is closest to the Earth, the distance between their centres is 225,000 miles, and the greatest distance is 252,000 miles.

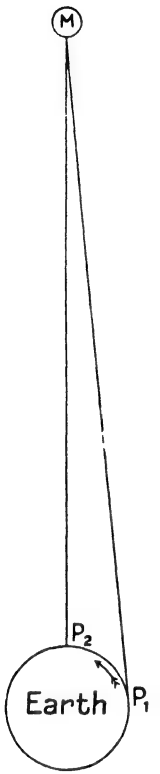
The difference is 27,000 miles, or more than 10 per cent. In the former case the apparent diameter of the moon in the heavens is 32′ 56″, in the latter case 29′ 31″, these two figures naturally differing by more than 10 per cent. It is not easy to observe this directly as we never see the two disks of the moon in the sky at the same time. However, the apparent diameter of the sun in the heavens is about equal to that of the moon. The diameter of the sun, too, varies according as the Earth is further from or nearer to the sun, by a little more than 3 per cent.

At some times the apparent diameter of the moon is slightly larger than that of the sun, at other times it is smaller. We shall see that with solar eclipses, when the sun, viewed from the Earth, is covered by the moon, this fact is of vast importance. If the moon, as seen from the Earth, is smaller than the sun, it is impossible for the solar eclipse to be total, even if from a certain point of the Earth the centres of sun and moon coincide; a "ring" of sun will then remain visible round the moon. We then speak of an *annular* eclipse. If, on the contrary, the apparent diameter of the moon is larger than that of the sun, a *total* solar eclipse may be occasioned; the duration of the total eclipse is longest when the moon is closest to the Earth and the sun farthest away from it so that the apparent diameter of the moon exceeds that of the sun by the greatest amount.[1]

The distances we just now mentioned are from the centre of the Earth to the centre of the moon. It follows that a certain point of the Earth's surface may get somewhat nearer to the moon than the "minimum" distance of 225,000 miles. For, if the moon rises at a certain point on Earth, it is farther away from this particular point than six hours later when it has reached its highest position in the heavens (*see* Fig. 19). This will best be understood if a point is chosen on or near the Equator. There the phenomenon will be most clearly perceptible. The distance will be smallest when the moon

[1] It is true, that if the moon is nearer to the Earth, it moves quicker, but this difference in velocity does not counterbalance the greater difference in apparent size of moon and sun, so that the duration of the totality increases.

is in the Zenith. At that moment our point will be one radius of the Earth nearer to the moon than the Earth's centre. In the case of the moon (and of the moon only), this difference may not be neglected. For our point is now about 4,000 miles nearer to the moon than the centre of the Earth. Calculated on the minimum distance of 225,000 miles, this is again a difference of almost 1·8 per cent. This entails a fresh increase in the moon's apparent diameter, which from 32′ 56″ may now further extend to 33½′. The difference can only be as great as this if the moon is exactly in the Zenith, but everywhere on Earth the moon is slightly larger when high in the heavens than when near the horizon. We have already explained (page 76) why, owing to a remarkable optical illusion, the reverse seems to be true.



P_1 is a point at the Equator at the moment that the moon "rises." Six hours later this point will have reached P_2 and will see the moon in the Zenith. Obviously, it is now about one Earth radius nearer to the moon.

The apparent size of the moon, as seen from the Earth, may therefore, within the course of a few hours (from low to high position), increase considerably and subsequently (from high to low position) decrease again. Thus it may sometimes happen that in the morning the apparent diameter of the moon is somewhat smaller than that of the sun, somewhat larger in the afternoon and somewhat smaller again towards the evening. This, by the side of the three well-known forms of solar eclipses (partial, annular and total), may give rise to a fourth form, notably, *the annular and total eclipse.* Such an eclipse is annular in those regions of the Earth where it occurs in the morning or towards the evening, total where it is visible in or about midday. A solar eclipse of this sort occurred on April 17, 1912: it was annular not long after midday in France, Belgium and the South of Holland (with a film-like ring), but total in N.W. Spain precisely at midday. It stands to reason that at a given place a solar eclipse will always be either partial, or annular, or total. This does not alter

the fact, however, that at the beginning of the eclipse at a certain point the diameter of the moon may be large enough for a total eclipse, but may have ceased being so at the critical moment; naturally, the reverse may equally well occur.

From the above it follows that the distance to the moon may, under certain conditions, drop to about 221,000 miles, that is the distance measured to the centre of the moon. The middle of the lunar disk that we see is, however, as all of you will understand, one radius of the moon or almost 1,250 miles nearer to the Earth. Hence, given the most favourable conditions, the surfaces of moon and Earth may approach to within about 220,000 miles of each other.

The Moon's Axial Rotation

Let us continue our investigation into the moon's motions. Does the moon also rotate round an axis? If we watch the lunar disk, on which we clearly discern mountains and dark plains (the so-called *maria* or oceans), we perceive nothing of any axial rotation. And from day to day the same part of the lunar disk, as seen from the Earth, is occupied by the same mountains and plains.[1] The moon continually presents the same side to the Earth. The other side of the moon's surface we do not know. From this it seems to follow that the moon has no axial rotation. But let us not be too rash in drawing conclusions. Astronomy is a science, we have repeatedly seen, where one must pick one's way carefully. We shall therefore go into the matter more closely.

To this end we place a large globe on a table in the middle of a square room. On the floor we draw a circle as large as possible round the Earth and now ask a friend to walk slowly along the circumference of the circle round the Earth, however, without revolving about his axis. By this we mean that when starting on his walk facing North, that is, with his face to the Northern wall of the room, he must keep his face in the same direction throughout his

[1] Apart from minor shiftings owing to what is known as libration. *See* page 145.

motion round the Earth. He begins by walking forwards with the globe on his left, then edges to the left, walks backwards, completing his round by moving to the right. From the Earth one has then successively seen his left side, his back, his right side and his front. The moon does not make its revolutions like this. We now get our friend to repeat his walk round the Earth, but this time with his face continually towards the Earth. This time his front has faced all sides of the room, but from the Earth his back has not been seen at all. How is that? Well, in keeping his face turned towards the Earth, our friend has made one complete revolution round his axis! For has he not been facing all sides of the room while moving round the Earth? And his rotation was effected in the same time as his revolution! So there you are. And both movements took place in the same direction, anti-clockwise.

So now we know exactly how the moon turns about the Earth. The fact that the moon, while turning round the Earth in slightly less than a month, always presents the same face to the Earth, is due to its completing one rotation round its axis in exactly the same time. It might be thought that this is a very queer coincidence indeed. How is it possible that these two movements coincide so exactly? This is no mere chance. At present the moon is a barren and dreary waste, as we shall see further on. But hundreds of millions of years ago this was not so. It then span on its axis much faster, and the rocks of the moon were still in a liquid state. The Earth caused a tide in those fluid masses, a tide which, owing to the far greater attractive pull of the Earth and the smaller pull of the moon, was much more powerful than the tides we know on Earth. And the moon was forced to revolve below this tide, as the Earth does at present twice in 24 hours below our tide. And the much heavier tidal wave on the moon had a far greater arresting effect than our tide has, also because the moon's mass is so much smaller. This brake never stopped its work until the moon rotated round its axis in the same time

as it revolved about the Earth, always presenting the same face to the Earth. From that moment the tide, too, remained stationary at the same spot "under the Earth," at the same spot on the moon. All further arresting effect was then out of the question.

The moon, then, rotates round its axis in the same time as it takes to revolve about the Earth. Hence, day and night on the moon each last about 14 days. The Earth, as seen from the moon, is practically a motionless disk in the heavens.

The Moon's Path round the Earth. The Phases of the Moon

But let us return to the moon's motion round the Earth. We know that the moon turns round the Earth in slightly more than 27 days (sidereal revolution), but we are still ignorant as to the plane in which this happens. Let us assume, for the moment, that it is the same plane as that of the Earth's orbit round the sun, the ecliptic. We shall see later that this is nearly, but not quite, true. (In reality the two planes make an angle of about 5°, that is $\frac{1}{18}$ of a right-angle.)

We re-enter the room in which we experimented on the seasons and the aspect of the heavens in summer and winter. A few alterations are necessary: the room must be enlarged on all sides; the Earth's orbit must be extended accordingly and we must, moreover, see to it that a distance of one yard is left between the Earth's orbit and each of the four walls. We again raise sun and Earth 8 inches above the floor in a perpendicular direction, and take a marble, our moon, which by some mechanism is fitted so as to be at a distance of 20 inches from the Earth while circling round it in a horizontal plane on the same level as the Earth, i.e. at 8 inches from the floor. The Earth, as we set her in motion, travels in a horizontal plane (the ecliptic) 8 inches above the floor round the sun. We have arranged that the plane of the moon's orbit round the Earth coincides with the ecliptic. Should we lower sun, Earth and moon 8 inches, the moon's

orbit would run flush with the floor, and we might then represent it by a hoop a little more than one yard in diameter, let into the floor. But we prefer to have all movements take place at 8 inches above the floor.

The moon's orbit, as we have seen, is, in our model, in the plane of the ecliptic, and, we repeat, *this is not quite correct.* Yet the difference from the real state of affairs is, relatively, so slight that many phenomena must well-nigh appear as they do in reality. We shall presently see what changes are effected if we give the plane of the moon's orbit its right inclination of 5° to the ecliptic.

We place our Earth near wall No. 1, with its axis pointing towards that wall: its position on December 21. The moon is now set turning about the Earth, while the Earth is kept stationary with regard to the sun. The moon turns anti-clockwise. We now first take stock of the situation when the moon is nearest to wall No. 4, that is at the moment when the line moon-Earth is perpendicular to the line Earth-sun. We switch on the sun and put out all other lights. Now the moon does not give out any light of its own, but the sun, a tremendously white-hot sphere, does; so do the stars, which, as we shall see later, are bodies like the sun, but situated at far greater distances from the Earth. The moon, on the contrary, is a cold, dead body, which even in the coldest winter night does not radiate enough heat for us to perceive with the unaided senses. The moon would, therefore, be dull and altogether invisible, even at night, were it not that the sun illuminated it. Our good old sun lets her rays play on the moon's surface and part of this fierce light is reflected to the Earth. It follows that, if only part of the face which the moon presents to the Earth is lighted by the sun, we shall only see that particular part of the moon. Now, we all know that the moon appears to us in phases; it may be full, or it may appear as a narrow or a broad sickle with the convex side turned either to the right or to the left, while for a short time in every month the moon is entirely invisible (new moon). We shall try to explain all

this by means of our model. You will see that this is quite possible.

We place our eye on a level with the Earth and look in the direction of wall No. 4. And behold—we see the moon in the sky, but it is only a half moon. Only its right half is illuminated—the situation as it is at first quarter. We now set the moon in motion in the proper direction, that is towards wall No. 1. The moon takes about one week to cover a quarter of its orbit (from a point as near as possible to wall No. 4 to a point as near as possible to wall No. 1). Now if we wish to ascertain how we see the moon during that time, the fact may not be overlooked that in the meantime the Earth keeps rotating round its axis in 24 hours in the same direction as the moon turns about the Earth. The moon, consequently, rises and sets every day; only, a certain point on the Earth's surface must turn on a little every day to "catch up" with the moon. Every day the moon rises and sets 50 minutes later, on an average. The real differences, owing to a number of circumstances, vary widely; in this country they vary between 10 minutes and 1½ hours. But the moon never rises or sets less than 10 minutes or more than 1½ hours later than the preceding day. We shall, for the moment, not trouble about the Earth's axial rotation, and look from the Earth to the moon while it travels in the direction of wall No. 1. And what do we see? We see the moon grow in size; the part illuminated by the sun and visible from the Earth is gradually increasing. The moon is now approaching the point nearest to wall No. 1, so that moon, Earth and sun are almost in one line. At this moment a small strip on the left part of the moon becomes darkened. It rapidly increases in size as the moon travels on, until at last, when moon, Earth and sun are in one line, the whole moon is invisible. *It is completely eclipsed.* And we are not at all surprised to see this happen in our model. For we can see exactly how everything comes about! The moon is in the shadow (umbra) of the Earth, and our electric lamp (the sun) cannot shine through our Earth.

The only thing we may wonder at is why the moon is not eclipsed at *every* full moon. For we know that eclipses of the moon are of rather rare occurrence. We shall presently see that this is exactly because the plane of the moon's orbit does not concide with the ecliptic. Only when a full moon is in or near the plane of the ecliptic, does an eclipse of the moon, or *lunar eclipse*, occur. It now also becomes clear whence comes this name—ecliptic—for the plane of the Earth's orbit!

In the meantime the moon has travelled on. Its left part is again struck by the sun's rays and it is not long before the whole moon is illuminated again. The lunar eclipse is over. The moon is now heading for wall No. 2 and we can clearly see its right half decline gradually, until, after another week's time, when the moon has again covered one quarter of its orbit, only the left half is visible. It is then *last quarter*. We remember that at *first* quarter only the *right* half was illuminated. As the moon travels on, now making for wall No. 3, that is in the direction of the sun, the visible crescent is getting smaller and smaller, finally to disappear altogether. It is the *new moon* --about one week after last quarter. And looking from the middle of the Earth we actually see our marble, the dark moon, travel across the sun from right to left. The sun is now hidden from view; it is entirely obscured (or a small ring of sun is left round the moon: *annular eclipse*).

If we raise or lower our eye a little the sun re-appears partly; at these points of the Earth's surface there is only a partial solar eclipse: the marble is too small to cover the whole Earth with its shadow. And still a little higher or lower the sun is not eclipsed at all; there we see the whole disk of the sun above or below the moon. At the point where the solar eclipse was total this total eclipse only lasts a couple of minutes: the moon glides across the solar disk and leaves it on its left. The sun is now as brilliant as ever and of the unilluminated lunar disk (new moon) there is no trace. We need hardly point out that in reality solar eclipses

are not the rule, but exceptions, because the moon will as a rule *not* be in or very near to the ecliptic. But if this *does* happen, a lunar eclipse is followed by a solar eclipse a fortnight later.

So we have seen that lunar eclipses are only possible at full moon, solar eclipses only at new moon. The moon proceeds on its way and after one or two days a small crescent again becomes visible on its right half, which grows from day to day until, about a week after new moon, it is again first quarter.

This is all much simpler than the explanation of the seasons. It may be explained to a child of six by means of a glow-lamp, a ball and a marble.

A good deal more may be learned from our model, which, though still imperfect, represents actual conditions fairly accurately.

Position of the New Moon

It is not difficult to see that the *new* moon, at all points of the Earth and at any time of the year, must describe about the same apparent path in the heavens as the sun. Only, we cannot *see* the new moon, except sometimes for a short period during a solar eclipse. One other point should not be overlooked here: the vault of heaven seems to turn from East to West every 24 hours. This, as we know, is a consequence of the Earth's axial rotation from West to East. During these rotations the sun lags behind, almost one degree of arc every 24 hours ($360^\circ : 365$). It seems to travel among the stars from West to East. Every day the stars gain about 4 minutes in western direction, as we already know. This difference must be greater in the case of the moon. For the latter turns in a little less than a month about the Earth from West to East and consequently every 24 hours the moon lags behind the stars about 13° of arc. Hence, compared to the daily apparent movement of the sun from East to West: the moon lags behind about 12° every 24 hours. If, therefore, the new moon is exactly

on one line with the sun (solar eclipse) at noon it will, when the sun sets at 6 o'clock, have lagged behind the sun about 3° and set about 10 minutes later. The new moon does, therefore, indeed describe about the same apparent path as the sun, rising in the East and setting in the West, but it goes a bit slower.

Position of the Full Moon

The full moon, as seen from the Earth, is, at all times of the year, in a position opposite to the sun, with the Earth in between. From this it follows that the full moon must always rise at about the same time as the sun sets, and vice versa. It describes (one glance at the model will make it clear) at all points of the Earth and at all times of the year, about the same path as *the sun did half a year before. This means that in our country the full moon is high in the sky in winter and low in summer.* It is curious what a small number of people are aware of this: ask anyone you meet daily! Another conclusion to be drawn is that the full moon, during the arctic night, does not set at the Poles; within the Polar circles we may witness not only the midnight sun, but half a year later also the "midday full moon." It will now also be clear that in the region we live in, the full moon is much longer above the horizon in winter than in summer. Naturally, in the tropics the behaviour of the full moon is far less subject to variations in the course of the year.

Position of the First Quarter

And what about the *first quarter*? The model again supplies the answer. *The moon at first quarter takes up the same position in relation to the Earth as the sun three months later.* From this general rule the path of the moon at first quarter can be deduced for all seasons for any part of the Earth. In our country first quarter is high in the sky in spring, low in autumn. In summer and winter the position is at medium height.

Position of the Last Quarter

A similar rule must apply for the *last quarter*; it is as follows: *The moon at last quarter takes up a position in relation to the Earth as the sun three months earlier.* In our country, therefore, last quarter is low in spring, high in autumn.

On the Southern Hemisphere and in the Tropics

Like the sun, the moon, to an observer on the Southern hemisphere, shows the reverse behaviour as on the Northern hemisphere.

On the Northern hemisphere sun and moon are seen in the South, on the Southern hemisphere in the North. From this it follows that our Southern brethren see the quarter moons, so to speak, from the other side. At first quarter they see the *left* half (instead of the right half) of the moon illuminated; and at last quarter the right half. In the tropics, a medium condition must occur, which is indeed the case. When the moon rises at first quarter, the upper half is seen illuminated, at moon-set the lower half; for last quarter the conditions are reversed.

This has brought us to the end of our investigations with the moon's orbit in the same plane as the ecliptic. So we must now give the moon's orbit its proper inclination and see what changes are wrought.

The Inclination of the Moon's Orbit

We re-enter our experimenting room. Sun, Earth and moon are lowered until their centres are flush with the floor, in the ecliptic. We take up our position near wall 2, the position of the Earth on March 21. All mechanisms are off. We now assume that the moon's orbit round the Earth is represented by a hoop let into the floor. This would be correct if the moon's orbit coincided with the ecliptic. But since they do not, we shall have to adjust the position of the moon's orbit, by giving it an inclination of 5° to the ecliptic. We take hold of the hoop *somewhere* and raise it slightly on that side. Mind, the hoop is raised on *that side only*, the other half makes a corresponding dip.

Actually, what has happened is that the hoop has turned round an axis lying in the plane of the ecliptic and in the centre of which is the Earth. The reader will be kind enough to believe that our equipment makes all this possible. And he must allow us further to draw on his imagination in asking him to assume that the floor is of glass and that the hoop was tilted along the line Earth-Sun. If now we place the moon on the same line, she will be 5° above the sun (seen from the Earth).

The sun is switched on again. It is new moon and yet there is no eclipse of the sun. If the moon were visible from the Earth it would be seen to travel from right to left above the sun. The moon continues its course along the hoop, gradually dropping towards the ecliptic from the North until, at first quarter, it cuts the ecliptic. The moon travels on to full moon, continually getting more South of the ecliptic until, at full moon, it reaches its lowest position at 5° below the ecliptic. No trace of lunar eclipse now! The moon quite neatly keeps clear of the Earth's shadow, passing unobscured under it. The moon then begins to remount towards the ecliptic, cutting it at last quarter, and finally is again at its point of issue at 5° above the ecliptic (new moon). This, then, would be the situation if the Earth did not revolve about the sun. So that, to get an accurate representation of the facts, we must also make the Earth travel round the sun. But let us first have another careful look at the situation. The points where the hoop (the moon's orbit) cuts the ecliptic are called "nodes." In our example the "descending" node is at first quarter, the "ascending" node at last quarter. The line joining the nodes and hence also cutting the Earth, is called line of nodes. In our model the line of nodes is parallel to wall No. 2. The highest point in the moon's orbit is consequently nearest to wall 4, the lowest point nearest to wall 2. The two movements are now combined, i.e. the Earth is set turning about the sun, and the moon about the Earth. For the time being we must see to it that the line of nodes (L.N.) remains parallel to wall 2 while the Earth revolves about the sun. The highest point of the hoop will then remain nearest to wall 4, the lowest nearest to wall 2. The Earth now travels from vernal equinox to summer solstice, carrying the moon's orbit (the hoop) along with it. Three months after the vernal equinox the Earth has arrived at the summer solstice. Now what has happened to the moon during that time? We have seen it make a complete round of the hoop every 27 days (this being the length of the sidereal revolution. In three months it has made 3¼ of those revolutions; at the same time it has completed about three synodic revolutions; for the third time since the vernal equinox its position, as seen from the Earth, is the same in relation to the sun.

What has now finally become the situation at the summer solstice? Let us suppose that at the vernal equinox it was full moon; at about the summer solstice it will therefore again be full moon. But the line of nodes still runs in the same direction, that is parallel to wall 2. The highest point in the moon's orbit is still nearest to wall 4, the lowest nearest to wall 2. So now, at the summer solstice, the line of nodes is in the direction Sun–Earth! The full moon is consequently at or very near to the ascending node, so that a lunar eclipse is possible and even very probable. And a fortnight later the new moon will be very near to the descending node and then presumably occasion a solar eclipse!

The key to the situation is here the invariable direction of the line of nodes in space, the invariable position of the moon's orbit, of our hoop, in the universe. This strongly reminds us of the fixed position of the Earth's axis! For the very reason that its position is fixed in space, the line of nodes continually changes its position in relation to the line Earth–Sun! At the autumnal equinox the line of nodes will again be perpendicular to the line Earth–Sun. Solar or lunar eclipses are then out of the question. But at the winter solstice the line of nodes will again coincide with the line Earth–Sun and the full moon may then be eclipsed in the descending node, while the new moon may eclipse the sun in the ascending node!

The above will have shown you that solar and lunar eclipses can only occur in two periods of the year which are about half a year apart. And it is further clear from our model that, if any phase of the moon, at a certain moment, occurs at 5° "above" the ecliptic, the same phase must be *in* the ecliptic three months later, and 5° "below" the ecliptic after another three months.

The Turning of the Line of Nodes

All we have so far seen in our model with respect to the moon, however, does not fully represent conditions. Our model is not quite perfect, for the *line of nodes does not remain parallel to itself throughout the year.* I must confess that Nature does not make it easy for the readers, but with good will and a little patience anybody may get to the bottom of it. And he that finds it too involved, need have no scruples about skipping a few pages!

In 18⅔ *years the line of nodes makes one complete clockwise revolution!* Hence, at the summer solstice we may not leave the hoop of the moon's orbit in exactly the same position as near the vernal equinox. The difference *is* slight, but a difference there is all the same. The angle which the hoop makes with the floor remains, unchanged, 5°. But the line of nodes has turned

almost 5° clockwise round the Earth as centre. The points where the hoop intersects the floor have shifted, clockwise, almost 5° of arc (Fig. 20). These 5° of arc in three months are the direct outcome of the rotation of the line of nodes in $18\frac{2}{3}$ or $\frac{56}{3}$ years. This is $\frac{3}{56} \times 360°$ or about 19·3° in one year, and consequently almost 5° in three months.

The changes in the position of the moon's orbit can be best conceived if we imagine that the line of nodes in the floor slowly turns clockwise in the plane of the floor. The centre of the line of nodes, of course, remains in the Earth. For, with the Earth, this line revolves round the sun. The Earth's motion round the sun is counter-clockwise. Now, while the Earth *with* the line of nodes revolves in this direction round the sun, the direction of the line of nodes not being influenced in any way by this movement, the line of nodes itself has a slow, independent movement of its own in the opposite direction. This line of nodes may also be conceived as a stick with a knob at each end (the nodes).

Let us take a different example from the one just considered, and suppose that at the point of the vernal equinox the descending node (knob D) was pointing in the direction of the sun, that is towards wall 4. Knob D will then no longer point exactly to wall 4 at the summer solstice, but will have turned almost 5° in the direction of wall 3. At the autumnal equinox knob D will have a "deviation" of almost 10°, at the winter solstice almost 15°, and when the Earth has returned to the vernal equinox, the deviation of knob D will have grown to almost 19° 18′ in the direction of wall 3. A fresh conclusion may now at once be drawn: About 19 days before (in this period the Earth travels about 18° round the sun), when the deviation of knob D was over 18°, there must have been a moment when knob D again pointed straight to the sun, in other words that the position of the line of nodes with regard to the sun was identical to that at the point where we began, the vernal equinox. (*See* Fig. 20.) Accurate calculation shows that this moment occurs about 18·6 days before the Earth reaches the vernal equinox again. *Hence, after about 346·6 days the node will have resumed the same position with regard to the sun.*

So, if the node is exactly on the line Earth–Sun, it will be again on that line after 346·6 days. It is but natural that this period of 346·6 days should have been called eclipse year. We have seen, then, that three of the four actors playing the leading parts in the eclipses, notably, the Earth, the sun and the node, are in their proper places. If now the fourth actor, the moon, which may of course be anywhere on the orbit and not necessarily at the node, were likewise on the line Earth–Sun (in the position of

new moon), there would be a total solar eclipse. If, however, the moon was exactly in the new moon position one eclipse year (346·6 days) before that moment, it cannot be new moon now, for an eclipse year does not contain a whole number of synodic lunar revolutions, which last 29 days, 12 hours, 44 minutes, 3 seconds each. The "same" eclipse configuration, therefore, will never recur after one eclipse year. This does not alter the fact, however, that both periods in every year in which eclipses

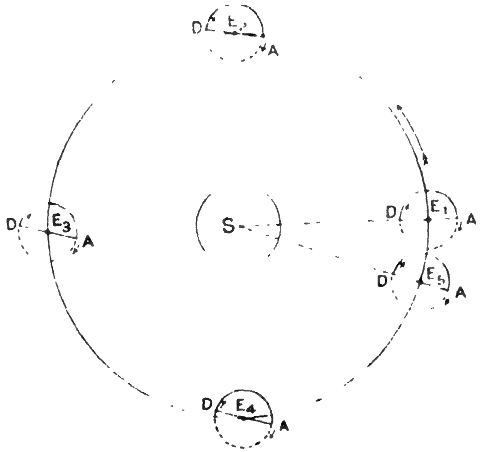


Fig. 20.

THE TURNING OF THE LINE OF NODES.

E_1 is the point of the vernal equinox. In our example the line of nodes now coincides with the line Earth Sun, the descending node being nearest to the sun (See text.) At point E_2 (summer solstice) the line of nodes has turned over an angle of almost 5 . At E_5, about 18·6 days before the Earth reaches the vernal equinox again, the line of nodes has turned over an angle of more than 18 and i again pointing in the direction of the sun. This last angle equa

are possible (*see* above) return after one "eclipse year," *so that the middle of these eclipse seasons falls almost* 19 *days earlier in every successive* (*solar*) *year.* After a little more than nineteen years these periods have cycled back to the same point (19 × 19 days is almost one year); after one half of this period has elapsed the eclipse seasons have changed places. These facts already afford a hint as to how eclipses can be foretold. Such predictions would be very easy if an eclipse year coincided exactly or approximately with a whole number of synodic lunar revolutions. But unfortunately this is not so. However, if a certain number of synodic lunar revolutions were to coincide with

a certain number of "eclipse years," our fourth actor, the moon, would be in the position of new moon again after the lapse of such a longer period, so that a solar eclipse at the beginning of such a period would be exactly repeated at the end of it. Now, it actually transpires that 223 synodic lunar revolutions (6585·32 days) equal about 19 "eclipse years" (6585·78 days). After $6585\frac{1}{3}$ days or 18 years 11 days and about 8 hours it will again be new moon (or full moon, if it was full moon at the beginning of the period). The node, too, will again be in the same place "to a hair." How this affects the repetition of the solar and lunar eclipses and their prediction, will be seen in the next chapter. But it will be clear to the readers that after 18 years, 11 days, 8 hours, about "the same" eclipse is repeated. This period is called the *Saros*.

The Accurate Position of the Moon in the Sky

We must say a few words on the influence of the movement of the nodes on the position of the moon in the sky. If, on December 21, the line of nodes is exactly perpendicular to the line Earth–Sun, with the ascending node at first quarter and the descending node at last quarter, and if, moreover, it happens to be full moon on that night, the full moon will, on the northern hemisphere, reach its highest position in the sky. In London it will then be able to ascend as far as about $66\frac{1}{2}°$ above the horizon, 5° *higher than the sun can ever attain!* There is then, at Lat. $28\frac{1}{2}°$ N., a kind of tropic for the moon, where it is just able to reach the Zenith. And round the Pole, in Lat. $61\frac{1}{2}°$ N., there is a second kind of "polar circle," inside which the full moon does not set, so that a "midday-full-moon" can there be enjoyed. On the southern hemisphere the moon will then reach its lowest position everywhere. Inside a second polar circle in Lat. $61\frac{1}{2}°$ S. the full moon does not rise above the horizon.

This maximum ascension of the winter full moon in our regions is not fully reached the next year, owing to the turning of the line of nodes. After five years our winter full moon will be about in the ecliptic, after nine years about 5° South of the ecliptic. It will then be incapable of reaching a higher position in our winter-sky than $56\frac{1}{2}°$. What bad observers we are, all of us! How few of us will have observed that the position of the winter full moon changes considerably in the course of ten years, not less than 10°! And, naturally, these changes are not confined to the winter full moon. The mean "highest" altitude of the full moon on June 21 is $14\frac{1}{2}°$ above our horizon, the same as that of the sun on December 21. This position of the moon varies from $9\frac{1}{2}°$ to $19\frac{1}{2}°$ in nine years. This is a much greater

proportionate difference than in the case of the winter full moon. Which of you has ever observed this very striking phenomenon? Who has ever seen a full moon near London at the highest point of its apparent path in the heavens at less than 10° above the horizon? The last time this occurred was in 1932. If such an extreme position has been reached, it is 18 to 19 years before it is repeated. Needless to say that for all phases of the moon, at any point on Earth, a corresponding variation in altitude of 10° on a certain date occurs over a full period of 18 to 19 years.

CHAPTER III

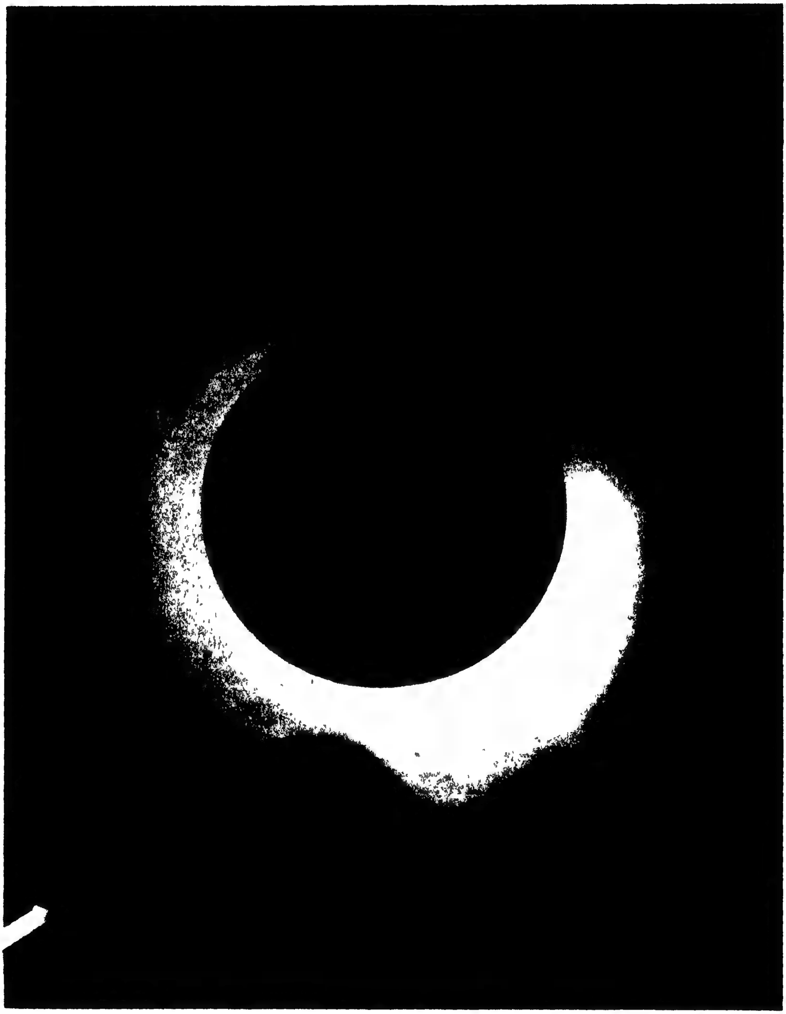
SOLAR AND LUNAR ECLIPSES

Solar Eclipses

The sun is blazing high in an azure, cloudless sky. There is nothing in the atmosphere to suggest that anything special is about to happen. The aspect of the heavens is the same as on any other fine summer day. But people know: there is going to be a total solar eclipse. And so they are anxiously awaiting the coming event. Exactly at the moment predicted by the astronomers a small dent is noticeable in the solar disk, to the right as seen from the Northern hemisphere, to the left from the Southern hemisphere. As we watch through our dark tinted glass we see this dent grow in size until, after a little more than half an hour, it extends to the middle of the sun. Up to that moment the scene has roused little more than ordinary interest; the word "imposing" can hardly be applied as yet. But from the moment the moon has covered more than half of the solar disk, things take on a different aspect. The daylight wanes perceptibly; what is left of the sun's rays gives less heat, shadows acquire sharper contours (because the source of light causing them has become less wide). The wind rises (as a result of variations in temperature), the very colour of the sky seems to change. Nature has doffed its bright apparel and becomes ominous in appearance. It might be imagined that a heavy thunder-storm is about to break loose. The sun has now dwindled to a narrow crescent, darkness is closing in, the birds of heaven seek their nests, domestic animals their respective homes. Not far from the sun we see a bright "star," the planet Venus, appear in the sky, perhaps also a second: Mercury. The crescent of sun has now narrowed

down to a mere strip, and at that moment thin dark stripes seem to move over the ground (their origin is uncertain). A last flicker of light and then darkness reigns. What we now behold keeps us spell-bound while it lasts. Everybody stands watching the brilliant spectacle motionless and with bated breath. On all sides the heavens are strewn with luminous stars; the darkness is not complete, it is more like a bright moonlit night, but the transition from the last bit of sunlight to totality is striking. The spot where a short time ago the sun was still shining, is now occupied by the black disk of the moon surrounded by a weak halo, the "corona" of the sun. This corona presents a splendid sight indeed! (*See* next page.) It is different in form and intensity with every new eclipse. It is *always* there, but we, ordinary humans, can only *see* it when the rest of the sun is eclipsed. The spectacle lasts two, three, at most seven to eight minutes; then the Western horizon is suddenly lighted up and a fraction of a second later the first ray of the sun flashes down (from the right side)—totality is over, the moon's shadow flitting in Eastern direction across the Earth's surface. The second half of the eclipse is the exact counterpart of the first. Then, as the last bit of moon leaves the solar disk, the eclipse is a thing of the past.

The spectacle of a total solar eclipse under favourable weather conditions is of unforgettable grandeur. It never fails to make an indelible impression on whoever may behold it, whether he be learned or simple in mind, civilized or savage. Centuries ago people were frightened when a total solar eclipse occurred, and even in our days the phenomenon does not fail to fill the minds of backward tribes with terror and dismay. At present its occurrence is enjoyed by civilized people as one of the finest—if not the finest—thing nature has to offer to mankind. Besides, it rightly inspires people with profound admiration for the science of astronomy, which makes it possible to predict the phenomenon and its entire course many years in advance with *infallible certainty to within some seconds.*



CORONA OF THE SUN DURING THE TOTAL ECLIPSE OF 1919.
Photo A. C. Crommelin, Greenwich Observatory.

Total solar eclipses are not so rare as is often believed. Eleven to twelve total solar eclipses occur in the course of eighteen years. But at any particular spot on Earth a total solar eclipse is extremely rare: on an average the same spot will see only one total solar eclipse in more than two centuries.

A solar eclipse is total where the umbra (shadow cone) of the moon touches the Earth. At any given moment this will only occur on a very small part of the Earth's surface. The point of the shadow cone only just reaches far enough and sometimes—when the eclipse is annular—does not even touch the Earth at all. On the Earth's surface the shadow cone presents a practically circular cross section: at a certain moment the sun is completely obscured on a more or less circular part of the Earth's surface with a diameter ranging from 0 (if the top of the cone just touches the Earth's surface) to at most about 190 miles. Owing to the motion of the moon round the Earth this spot moves fast across the Earth's surface, from West to East. Hence on a strip of Earth running from West to East and having a width ranging from some miles to about 190 miles, the eclipse is total. It begins at some point on the Earth where it is sunrise and ends somewhere to the East of the first point at sunset. To the North and South of this strip the eclipse is not total, but partial. The further North or South we go, the smaller the part of the sun that is obscured, until at last only a tiny "cap" on the Northern or Southern edge of the solar disk is eclipsed. Beyond these points there is no eclipse at all, since the moon, at "new moon," is slightly below or above the sun. We have already seen that the apparent position of the moon in the sky largely depends on the place from which it is seen on Earth: what we told you about the eclipses confirms this. The strip of the Earth's surface where at least a partial eclipse may be seen is very wide; it may extend from the Pole to the Equator.

A total solar eclipse on Earth, even under the most favourable conditions (which are *never* fully attained in practice), cannot last longer than a little over $7\frac{1}{2}$ minutes.

And this is only possible in the tropics[1] when in the middle of the eclipse the sun is near the Zenith, the moon is as close as possible to the Earth and the Earth is as far as possible from the sun. Practically speaking, a total eclipse of more than seven minutes is of extremely rare occurrence. Here follows the duration of totality of a number of future solar eclipses expressed in minutes:

June 8, 1937 : 7·1	Feb. 4, 1943 : 2·5	Nov. 1, 1948 : 1·9
Oct. 1, 1940 : 5·7	May 20, 1947 : 5·2	Feb. 25, 1952 : 3·0
Sept. 21, 1941 : 3·3		

It stands to reason that these maximum times only hold good for the middle of the totally obscured strip of Earth—towards the edges the totality gradually decreases to 0. Moreover, the duration of an eclipse will as a rule be shorter in those regions where it occurs early in the morning or late in the evening, because, as we know, the moon is then somewhat farther away.

We must now say a few words about the annular solar eclipse. What causes it we already know. This kind of eclipse is also a central one (that is to say, the place where we are on Earth, the centre of the moon and the centre of the sun are in one line), but the top of the shadow cone of the moon does not reach to the Earth, because the moon is too far off or the sun is too near, or both. The course of the eclipse is the same as that of a total one. But unfortunately the solar corona is not visible. A ring of sun remains visible round the moon and the light from this ring creates enough glare to obscure the faint corona. This ring (as seen from the Northern hemisphere) is at first very narrow on the right edge of the sun and somewhat wider on its left side. But gradually conditions are reversed, because the moon travels from right to left. An annular eclipse can, at the utmost, last a little over 12 minutes;

[1] The duration of a total eclipse is longer in the tropics than elsewhere because the rotational velocity is greatest there. At the Equator it is almost 17½ miles per minute. But the moon's umbra moves in space at the rate of about 30 miles per minute *in the same direction*. Hence, the swifter the rotational velocity the less the moon's umbra is displaced in relation to the Earth's surface.

during that time the whole lunar disk can be seen against the solar disk. The number of annular eclipses is about 1½ times that of the total ones; in other words, the shadow cone of the moon is more often too short than long enough to reach the Earth's surface. The strip of Earth where the eclipse is annular may be some 60 miles wider than in the case of a total eclipse. Beyond this area an annular eclipse presents the spectacle of a partial one, which is not fundamentally different from a partial eclipse outside the totality area of a total eclipse.

We mentioned above that the moon's shadow travels across the Earth from West to East. Owing to the varying position of the plane of axial rotation of the Earth in relation to the line joining the centres of sun and moon on different dates, this "central" line (axis of the moon's shadow) may, at a certain point of the Earth's surface, run from South-West to North-East, or from North-West to South-East.[1]

We already observed that it may occur very rarely that an eclipse somewhere on Earth begins as just annular, then becomes just total, and ends by being just annular again. I had the privilege once (on April 17, 1912) of witnessing such an eclipse in the southern part of Limburg (Holland) in a perfectly cloudless sky. I was exactly on the central line. In Spain this eclipse was total, in Limburg it was annular.

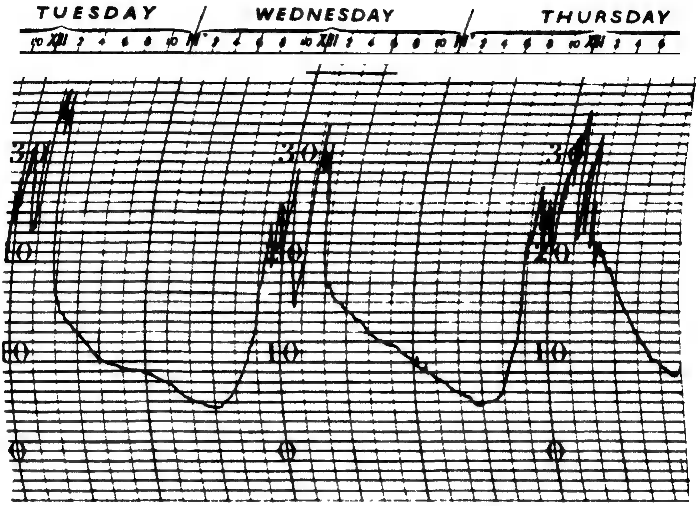
Everything happened just as in a total eclipse until the commencement of the total phase. Venus was clearly visible; the sky was very dark. At the moment of the "central eclipse" an extremely fine ring was seen to surround the moon, broken up in several places, however, into what is known as "Baily's Beads." These beads are due to valleys on the lunar surface, but they are magnified by optical illusion. So what we saw was more like a very thin string of bright beads surrounding the lunar disk than a ring. It

[1] Round about the vernal equinox the central line runs from South-West to North-East; round about the autumnal equinox from North-West to South-East; round about the summer solstice at first in North-Eastern, then in South-Eastern direction; round about the winter solstice at first in South-Eastern, later in North-Eastern direction.

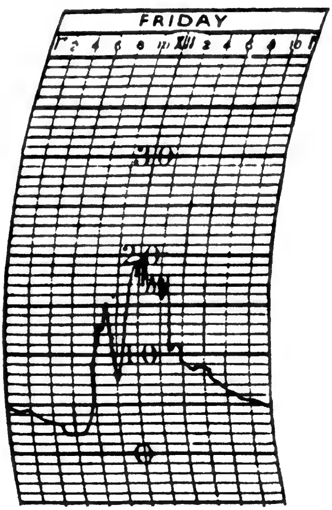
was a spectacle never to be forgotten, although it lasted only five seconds. During this eclipse the drop in temperature in the whole country, too, was very marked. At the maximum phase the sun's rays gave no appreciable heat. This is clearly to be seen from the thermogram of my self-registering thermometer printed on the opposite page, which was taken at Amsterdam right in the sunshine on that memorable April 17, 1912. Another thermogram taken in the same way is added, of the solar eclipse of April 8, 1921.

Partial solar eclipses which are not total or annular anywhere on Earth may also occur. The central line will then fall, as it were, North of the North Pole or South of the South Pole, hence outside the Earth. The top of the moon's shadow cone then passes "below" or "above" the Earth, without touching it. This happens if the moon, at the moment of new moon, is somewhat farther from the node.

The node moves but slowly in relation to the point of new moon. This displacement is 360° in one "eclipse year," which is about 347 days (*see* p. 131). This works out at $1^\circ 2'$ per day. Hence about 29 times as much, or about 30° in one synodic revolution of the moon. Now, as we shall see presently, there is a margin of no less than 36° in the case of a solar eclipse; that is to say, 18° to the right and 18° to the left of the node there may still occur a small partial solar eclipse in the neighbourhood of one of the Poles of the Earth. And thus, because the node is not displaced more than 30° between two successive new moons, it is possible that each causes a partial solar eclipse. The first will then be in the South of the Southern hemisphere, the second in the North of the Northern hemisphere. Or the other way about. The former case will present itself near the ascending node, the latter near the descending node. Such eclipses which follow about a month after each other, are not at all rare. No fewer than five solar eclipses may occur in one calendar year, although this is extremely rare. Four in one year, too, is exceptional. An example is: January 31, 1870, partial, South Pole; June 28, 1870, partial, New



Thermogram Richard, registered in Amsterdam in direct solar radiation on Wednesday, April 17, 1912. The previous and the following days have been added for comparison. The solar eclipse took place between noon and 2 p.m. Centigrade degrees



Solar eclipse in Amsterdam on Friday, April 8, 1921, about 10.

Zealand; July 28, 1870, partial, Siberia; December 22, 1870, total, Algeria. The second and third of these are examples of eclipses at successive new moons. It will be clear to you how exceptional the occurrence of two such pairs plus another solar eclipse in one calendar year must be.[1] It is impossible for a solar eclipse to occur less than twice in one year. They will succeed one another with an interval of a little less than half a year.

A solar eclipse, as we have seen, presents a different spectacle at almost any point on Earth where it is visible. On page 120 we saw that the same eclipse returns after 18 years, 11 days and about 8 hours. These eight hours, however, put a spoke in the wheel. For although it is true that the same eclipse will occur after that period, during those 8 hours the Earth will have rotated round its axis about 120° further to the East. The place where the eclipse is visible will therefore be more to the West. Example: August 7, 1850, total, Pacific Ocean; August 18, 1868, total, Red Sea; August 29, 1886, total, Gulf of Mexico; September 9, 1904, total, Pacific Ocean. Other example: February 22, 1849, annular, China; March 6, 1867, annular, Algeria; March 16, 1885, annular, North America; March 29, 1903, annular, China. The central lines of two such "successive" eclipses will as a rule intersect, so that for one tiny spot on Earth the prediction of a repetition after 18 years and 11 days holds good. But it will be clear that this period does not allow of very exact predictions being made. After 54 years, that is after three periods, there is better concord; the above example shows it, while it follows logically from the three times 8 hours. The eclipse will then occur on about the same meridians. But even then the eclipse is not *exactly* the same.

We can trace accurately why, and in how far, a solar eclipse which is repeated after 18 years 11 days or after 54 years 34 days, differs from its predecessor. To this end we need but ascertain

[1] Curiously enough, this rare privilege was reserved for us in 1935. Solar eclipses on January 5, February 3, June 30, July 30 and December 25.

what the difference is between the 223 revolutions of the moon and the 19 eclipse years (*see* page 128). The node, at the moment of the 223rd new moon, has completed its 19th revolution in relation to the sun to within 0·46 day, and must therefore be in the immediate vicinity of the new moon. In regard to the sun the node makes a complete round of 360° in 346·6 days, hence in one day 360/346·6 or about 1° 2′, and in 0·46 day about 28′. This movement is clockwise, so that 223 synodic revolutions after a new moon exactly in the node, the moon will be 28′ from the node in clockwise direction. The moon, which moves round the Earth counterclockwise, i.e. from West to East, is then 28′ West of the node as a new moon. Yet this difference will by no means prevent another solar eclipse; on the contrary, the solar eclipse will strongly resemble that of 18 years, 11 days and 8 hours before. For, as we saw, a solar eclipse is caused near the node, if the new moon is not farther away from the node than 18°. This need not surprise us, if we remember that the moon at 18° from the node has covered $\frac{4}{5}$ of the way by which, from its greatest deviation from the plane of the ecliptic, it returns to the ecliptic, or, only $\frac{1}{5}$ of the path along which it is carried back to the point where its deviation from the ecliptic is greatest. It cannot, therefore, be at that moment very much above or below the ecliptic. Well, if a distance of 18° or 1080′ from the node does not prevent the occurrence of a solar eclipse, it is obvious that 28′ will make very little difference indeed. In addition, there is the fortunate circumstance that after the period of 18 years and 11 days the distance between Earth and moon is pretty much the same again. Consequently the duration of the eclipse will be practically the same, the more so as 11 days produce only a slight change in the distance between Earth and sun. The period of 18 years, 11 days and 8 hours was already known to the Ancients (from experience) and is called "Saros." So after each saros the new moon will be 28′ further West of the node. From this the following may be deduced with regard to the "repetition" of solar eclipses. At a certain new moon the moon will be 18 and some minutes East of the node. So there is no eclipse, the distance to the node being too great. One saros later the new moon will be 28′ more to the West, so that there will then be a small, partial solar eclipse near one of the Poles. This will be the North Pole if the moon is near the ascending node, the South Pole if near the descending node. We might call this eclipse a *new* eclipse, for it is the first of a "series." After each saros the eclipse returns, and at each following eclipse the moon is 28′ nearer to the node. After about 36 "sarosses" the moon has reached the node, while after another 36 sarosses it has moved so far from the node in Western direction that no eclipse is possible any more. Hence a "series" of

solar eclipses contains about 72 eclipses occurring 18 years 11 days and 8 hours one after another. After about 14 eclipses the moon is only 11° from the node, so that then either a total or an annular eclipse must occur. As we saw, the first eclipse is a small, partial eclipse near the North Pole if the new moon is near the ascending node; each subsequent eclipse will be slightly larger and reach somewhat more to the South. After about 14 eclipses there will be a total (or annular) eclipse in the North, then follow about 44 eclipses (total or annular) which occur more to the South every time, the twenty-second of them near the Equator, the forty-fourth near the South Pole. Then follow another 14 partial eclipses, gradually occurring more to the South and decreasing in size. With a new moon near the descending node the series is completed in the reverse sense. So this is how a repetition of the same solar eclipse after 18 years, 11 days and 8 hours must be conceived. The whole series is completed in about 1,300 years. But it is clear that now and then new series begin and that several series are running at the same time. If we consider all solar eclipses it transpires that more than 40 series are in progress at the same time. This is not at all surprising if you come to look at it carefully, for a saros contains 19 eclipse years and in each eclipse year the new moon must at least once be near enough to the ascending node and at least once near enough to the descending node to cause, somewhere on Earth at any rate, a partial solar eclipse.

A few words on the duration of a saros. We have taken it to be 18 years, 11 days and about 8 hours. But it should be pointed out that for the calendar year these 11 days may be 10 days, if in those 18 years there are five instead of four leap years. And in the neighbourhood of the centurial year 1900 (or 2100, 2200, 2300) they may become 12 days, if only three leap years have elapsed, for instance between 1889 and 1907, or between 1885 and 1903 (*see* the last example on page 139 and don't forget the date-line!).

In the case of solar eclipses in particular the Ancients, although they knew the saros from experience (the Babylonians, it seems, must be credited with its discovery), could not attain great proficiency in the art of predicting. The only thing they knew was that on a certain day, one saros-period after an eclipse, there was a *possibility* of another eclipse.

At present the eclipses are calculated *centuries* in advance, although a calculation accurate to within seconds—in con-

nexion with the extreme complexity of the moon's motions —cannot be made until some years before the eclipse takes place. Not only for the future, but also for the remote past eclipses can be calculated. The astronomer Oppolzer, with his pupils, made detailed calculations for all solar and lunar eclipses from 1207 B.C. to A.D. 2162, in all, 8,000 solar eclipses and 5,200 lunar eclipses.

Eclipses and Ancient History

The accurate calculation of the dates of solar and lunar eclipses in past ages may be of the greatest importance from a historical point of view. Thanks to solar and lunar eclipses a number of historical dates have been definitely established. This may be done in different ways. Of several peoples (Chinese, Persians, Babylonians, Greeks, Romans) chronological, historical tables have come down to us, containing the outstanding historical events, with their dates. That is to say, we can read there that in the year so-and-so of the reign of King So-and-so, or (with the Romans) in the year in which two given Consuls were in power, a certain historical event took place at a certain date. But this does not fix the dates definitely. For the reigns of the various sovereigns are often inaccurately known and the ancient calendars leave much to be desired. However, everything is settled by the fact that these tables often record solar and lunar eclipses. These enable us not only to calculate the exact dates now, long after the events, but they also afford us the opportunity of getting acquainted with these old calendars with all the errors and defects attaching to them, and of seeing how far they deviated from the natural calendar. Thus a chronological table can be completely checked up by the aid of some eclipses.

On the other hand, we possess a number of records of important historical events that coincided with a solar or a lunar eclipse. Thus, in the beginning of the sixth century B.C., a battle was fought between Medes and Lydians. Scarcely had the fight commenced, when a solar eclipse came to sow

dismay among the ranks. Formerly the day of this battle was not known accurately to within many years, but we now know that it took place on May 28, 585 B.C.

Another example is afforded by the siege of Syracuse by the Athenians. They were about to sail off with their fleet, when a lunar eclipse occurred. Frightened by the unusual phenomenon, they tarried for some time, which led to the complete destruction of their fleet by the enemy. This eclipse happened on August 27, 413 B.C. The solar eclipse mentioned in the Old Testament (Amos viii, 9) is probably that of June 15, 763 B.C. And thus we could go on giving other examples. To me, there is no section of the chapter on eclipses which is more interesting than this "backward calculation."

Lunar Eclipses

It is a calm, bright winter night, with a silvery full moon high in the sky. We are on the Northern hemisphere, on the outskirts of London. It looks as if the lunar disk were slightly obscured on its left side: particularly near its left edge the moon seems to be a little "soiled." This dinginess even appears to increase slowly. However, it is not very conspicuous. No one who does not pay special attention to it will be aware of anything out of the ordinary going on. What is this? On the left side of the moon, on the very spot where the soiling appeared, a dent becomes visible. The dent is clearly demarcated, yet not so sharply and not by such a rounded line as the moon's edge in a solar eclipse. A lunar eclipse has set in: as it increases and the "dent" gets larger, we see that its edge is formed by a faintly curved line, part of a circle with a radius considerably greater than that of the moon. This circle is the circumference of the Earth's shadow (shadow-cone): it is the shadow which the Earth, under the sun's rays, casts behind it into space. We can now clearly see that the Earth's shadow is round. With every lunar eclipse it is invariably round on all sides; so the Earth itself must also be round. This is one of the oldest,

one of the simplest and most convincing proofs of the Earth's spherical shape. We see with our own eyes that the Earth is round!

Thus the Earth's shadow travels from left to right across the lunar disk, or—to put it more accurately the lunar disk, in its course round the Earth, enters the Earth's shadow from right to left. As soon as one half of the moon is eclipsed, we are quite surprised to notice that the eclipsed part is again faintly visible as a ruddy-grey patch. As the eclipse progresses and the illuminated crescent of the moon is getting smaller and smaller and sheds less and less light, the eclipsed part gains in clarity. Its hue is now that of brass, copper, or ruddy; it varies with each eclipse.

When the illuminated sickle has grown very thin, it seems to adopt a slightly greenish-blue tint (complementary colour). Then, as the last speck of light has disappeared, the eclipse is total. The phenomenon, although not so thrilling and overwhelming as a total solar eclipse, is yet one of supreme beauty. The moon is now a ruddy *globe* in the heavens. To many a one it is much more like a globe than the uneclipsed moon, which we see more like a flat *disk*. The various hues are not equally distributed over the surface; where the disk is closest to the edge of the shadow cone the colour is lightest; the parts that have farthest penetrated the shadow are darkest. And as we already observed, the tint varies from eclipse to eclipse; sometimes the totally eclipsed moon is a bright yellow, so that at first sight it does not even differ materially from an ordinary moon; at other times it is dark ruddy or brown, or even *completely invisible*. This, however, like the bright yellow tint, is very exceptional. We shall presently see what these differences are due to.

We look about us at the starry universe. The heavenly bodies are scintillating as in a moonless night! At first, when the full moon was shining in all its glory, only the brightest stars were visible in the sky; in the vicinity of the moon not a single star was discernible. Now they are

glittering like diamonds against a dark background everywhere, even quite near the moon's edge. The totality of a lunar eclipse, under the most favourable conditions, can last more than two hours. There is therefore plenty of time to watch the spectacle at our ease. The moon is seen to move among the stars to the left, to the East. Star eclipses can now also be seen, that is to say, stars disappear behind the left edge of the moon and reappear at the right edge. Of course, this also happens when the moon is not eclipsed, but then it can only be observed in the case of very bright stars, other stars not being visible close to the moon. Moreover, an eclipse enables us to fix with much greater accuracy the moment of disappearance and reappearance of a star, which is of great importance to astronomers.

But all things come to an end, and therefore also a lunar eclipse. It is not long before the first bright ray of the moon strikes the Earth again from the left, presently, the strip of illuminated moon grows into a crescent, the crescent to a half moon, until after a little more than an hour the moon is completely "free" again, although its right half continues for quite a long time to have a certain "smudge" on it.

This, in brief, is the course of a total lunar eclipse. I have been able to watch the phenomenon at least ten times in my life. It is a pity that the weather is not always propitious but sometimes mars the effect. For, if the sky is overcast, the phenomenon, apart from a distinct darkening of the clouds, passes unnoticed. To watch it, one would then have to ascend above the clouds in a balloon or an aeroplane. A completely covered sky is a great disappointment, but it is nothing compared to that of many scientific expeditions who go to the uttermost parts of the world to see a solar eclipse, work there for months and months in order to erect their instruments with the greatest care, and then at the supreme moment the only observation they are able to make is that it is pouring with rain and pitch dark!

A partial lunar eclipse, especially if it only concerns less than one half of the lunar disk, is much less interesting. It is then only a small section of the moon that is obscured. But even then the circular shape of the Earth's shadow is distinctly to be seen.

I must mention a few other facts and details concerning the theory of the lunar eclipses. First of all this important fact: the whole number of lunar eclipses is smaller than the whole number of solar eclipses. There cannot be more than three lunar eclipses (three is very exceptional, so is one, two being the rule) in one calendar year, while there may also be years without any lunar eclipse. However, the number of lunar eclipses on one and the same spot on Earth is much greater than that of solar eclipses. That is because a lunar eclipse is a *real* phenomenon: the moon actually loses its light, being in the shadow of the Earth, that is, unable to receive and reflect the sun's rays. If on the outskirts of the town we build a big tower, which is visible from any part of the town, we shall be able to see that tower at night if it is floodlit. But if between the flood light and the tower a large globe is placed, so that the tower is entirely enveloped by the shadow of that globe, we see the tower obscured at the same moment everywhere in the town. It is the same with a lunar eclipse: *from all places on Earth where the moon is visible* (and this at a given moment is half the Earth's surface) *the lunar eclipse can be observed in the same way*, with this difference, of course, that the moon is seen at different altitudes. Since an eclipse lasts several hours and even the total phase may last more than two hours, while all the time the Earth rotates round its axis, the part of the Earth's surface where the eclipse can be seen, is more, sometimes considerably more, than one half. There are regions where the moon rises entirely eclipsed, so that people living there will only witness the second half of the drama, whereas in other places it sets, entirely eclipsed, so that people must content themselves with only seeing the first half. Some will even see as little as the mere beginning of the eclipse just

before the setting of the moon, still others only the very last bit, just after the rising of the moon.

It follows that of all lunar eclipses, especially the total ones (which last longer than partial ones), more than one half will be visible, or at least partly visible, to us. How different this is from the solar eclipses! The solar eclipse is not a "real" but only a perspective phenomenon. If in the case of the above tower I place a huge globe on one side of it, the tower will be invisible in certain parts of the town only. On the opposite side the tower will remain visible.

In a period of 18 years there occur about 28 lunar eclipses and about 43 solar eclipses. Sometimes one more, sometimes one less. If there are 29 lunar eclipses, twelve are as a rule total, seventeen partial. Of these 12 total lunar eclipses the same spot on Earth will see 3 or 4 completely, 5 partially, and 3 or 4 not at all. Do not forget that this "partial" visibility also includes cases in which the whole total phase, that is by far the most important part, is visible, while only the decrease or increase is wanting. This shows you that a "partially" visible eclipse may be almost as interesting as one which is entirely visible. Of the approximately 17 partial lunar eclipses occurring in a period of 18 years, one and the same spot on Earth will see 6 or 7 completely, 4 or 5 partially and 6 or 7 not at all. A given spot, therefore, will see $\frac{17}{24}$, that is more than $\frac{2}{3}$, of the total lunar eclipses entirely or partly; of the partial lunar eclipses only $\frac{11}{17}$, that is less than $\frac{2}{3}$. This tallies with what we had already found; the visibility of the total lunar eclipses is, relatively, a trifle better than that of the partial ones. The same spot on Earth, in a period of 18 years, will consequently see:

3 or 4	*total*	lunar	eclipses	*completely*
5	*total*	,,	,,	*partly*
6 or 7	*partial*	,,	,,	*completely*
4 or 5	*partial*	,,	,,	*partly*

In all, 19 or 20 lunar eclipses on the same spot in 18 years.

The above now also makes it clear why the saros (the period of 18 years, 11 days, 8 hours) is so much more useful for predicting lunar than solar eclipses. A large part of the Earth's surface does indeed see the eclipses as predicted by means of the saros. Only, here too, the odd 8 hours give

trouble. If the middle of the eclipse was visible at a certain place at 8 p.m., the same point will see it 18 years later at about 4 a.m. In this case both eclipses will be well visible in the winter, but in summer only the end of the first and the beginning of the second. And should the first be at 3 a.m., the second will not be visible at all. But after 54 years practically the same eclipse returns at the same place. Some examples may illustrate this: Total lunar eclipse on November 25, 1844, 0.14 a.m., *visible*; December 6, 1862, 8.10 a.m., *partly visible*; December 16, 1880, 4.8 p.m., *partly visible*; December 28, 1898, 0.56 a.m., *visible*. Second example: Partial lunar eclipse on January 17, 1851, 5.19 p.m., *partly visible*; January 28, 1869, 2.8 a.m., *visible*; February 8, 1887, 10.51 a.m., *invisible*; February 19, 1905, 7.30 p.m., *partly visible*. This last example at the same time shows how even after 54 years quite considerable differences in time may occur. We cannot repeat too often that the saros is only an approximate period.

A few facts have still to be explained. In the first place, why the total number of lunar eclipses is smaller than that of the solar eclipses. We know that both kinds of eclipses can only occur if the new or full moon is in or near the node. Well, in the case of solar eclipses there is somewhat more "play" than with lunar eclipses. For the relation between the sizes and distances of the three actors in the drama, the sun, the Earth and the moon, is such that if it is new moon at a distance of slightly less than 18° from the node, there may be still a tiny partial eclipse near the North or the South Pole. As we saw, this makes it possible for two successive new moons to cause two partial solar eclipses. But in the case of a lunar eclipse there is less scope, for if the full moon is more than 12° from the node, it passes over or under the shadow cone of the Earth. That is why two successive full moons can never both be eclipsed. You have only to draw a model in the proper proportions to see the truth of this.

We have also seen that on the side where the moon will soon enter the Earth's shadow, it first becomes some-

what "soiled" in appearance; the light on that side wanes. The reason of this is that the moon, before entering the shadow cone proper, that is the *umbra*, has first to pass the *penumbra* (partial shadow), a region where the sun's rays are only partly intercepted by the Earth. This may best be made clear in the following way. Every *lunar* eclipse on *Earth* is a *solar* eclipse on the *moon.* At the edge of the moon where we see the lunar eclipse take shape as a small dent, a total solar eclipse commences at that moment. But it will be clear to you that at that point of the moon there does not *at once* set in a total solar eclipse. The solar disk, as seen from there, has slowly disappeared behind the Earth; gradually the sunlight has decreased to total eclipse. This gradual falling off of the sunlight we see as a "soiling" of the moon.

It may also happen that the full moon just grazes, so to speak, the Earth's umbra and only passes through the *penumbra.* There will then, on a part of the moon, be a partial solar eclipse. These "penumbral eclipses" are not reckoned among the lunar eclipses proper, although they are sometimes very clearly to be seen. If we counted in all these "penumbral eclipses" (including those in which only a tiny portion of the moon sees a very small solar eclipse, so that to our eye a tiny little portion of the lunar disk gives a little less light) the number of lunar eclipses would compare much more favourably with that of the solar eclipses.

At the place where the moon passes through the Earth's shadow the diameter of the umbra is, on an average, almost $2\frac{2}{3}$ times as large as that of the moon (Fig. 21). We may notice this during an eclipse: the circumference of the Earth's shadow is part of a much larger circle than the moon's edge. Now if the eclipse is exactly in the node, the centre of the moon passes exactly through the centre of the Earth's umbra; the totality will then have its longest possible length (Fig. 21, 4). But also if the centre of the moon, in the middle of its path across the Earth's shadow, is not more than $1\frac{2}{3} \times$ the moon's radius (about 25′ above or below the centre of the Earth's

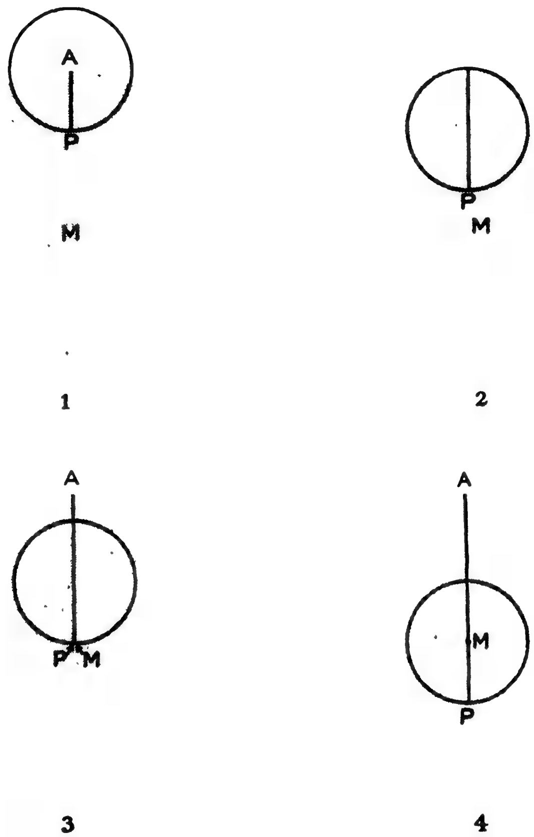


Fig. 21.
The "Size" of a Lunar Eclipse.

Drawings 1–4 represent the maximum size of four different lunar eclipses. The small circle is the moon; the large one the cross section of the Earth's shadow cone (umbra). The size of each of the eclipses is:

moon's diameter	,,	2.	,,	1·00
	,,	3.	,,	1·33
	,,	4.	,,	1·83

The moon traverses the Earth's shadow from right to left, its path being at the same time slightly oblique in upward or downward sense. In these sketches, however, the movement of the moon should be conceived as horizontal *from right to left.*

shadow), hence the same distance above or below the ecliptic a total lunar eclipse is still possible (Fig. 21, 2). The duration of totality will then, naturally, be very short only. The duration of a lunar eclipse and of its totality is further affected by the variations in the sun's and the moon's distance. Under the most favourable conditions for a lunar eclipse, there may still be a total eclipse if the moon is slightly further away from the ecliptic than the above-mentioned distance.

The reader will now also understand why it happens so often that 14 days after or 14 days before a lunar eclipse there is a solar eclipse. It is even possible that one as well as the other occurs, while one of the two solar eclipses is certain to happen. And finally, it will be clear that *if* two successive new moons each cause a solar eclipse, there must be a lunar eclipse between the two. And this lunar eclipse will invariably be total, which need not surprise us either.

A few words on the way in which the "size" of an eclipse is indicated. A given point P on the moon's edge has, at the moment of maximum eclipse, penetrated as "deeply" as possible into the shadow. The shortest distance from that point to the edge of the shadow cone we call *a*. Now the size of the eclipse is: *a* divided by the moon's diameter. Thus, if the size is 1·00, the moon will be totally eclipsed for one little moment (Fig. 21, 2). If the size is less than 1·00, the eclipse will be partial only (Fig. 21, 1). If the "deepest" point passes through the middle of the Earth's shadow the eclipse (with average proportions) is about $\frac{11}{1}$ or 1·33 (Fig. 21, 3). It stands to reason that the eclipse will be still larger if the moon's centre actually coincides with the centre of the shadow (Fig. 21, 4). Assuming average proportions, we then find for the largest possible eclipse about 1 : 1 or about 1·83.

I must now say something about the brass or copper colour which the moon adopts during the total phase. A setting sun on Earth becomes red-tinted; the red rays of the sun can best penetrate the Earth's atmosphere. In the mountains the peaks lying opposite the sun assume a ruddy tint (*Alpenglühen*). An analogous phenomenon occurs on the moon during a lunar eclipse, which, as we have seen,

is a solar eclipse to the moon. The sun's rays can no longer reach the moon. But round the Earth is the atmosphere: true, it is, comparatively speaking, a very thin layer, but still it is there. The red rays of the sun penetrate through this atmosphere and are "refracted" towards the moon. So, in a certain sense, during a lunar eclipse we see *Alpenglühen* on the moon. According as the Earth's atmosphere at the points grazed by the sun's rays—that is, where the sun rises or sets at that moment—is clear or laden with dust or ashes (especially after heavy volcanic eruptions), it will let through much or little light, so that the moon will be correspondingly bright or dull during the eclipse. Incidentally, it has transpired that Northern eclipses, during which the moon passes through the Northern part of the shadow cone, are darker than the Southern ones. It seems, therefore, that the atmosphere of the Southern hemisphere (more water, less dust) is more transparent than that of the Northern hemisphere.

As you are aware there is, on an average, one total lunar eclipse visible every three years from the place where you live (provided, of course, that the clouds are kind enough not to interfere). I need not here mention future eclipses; they are given in all almanacs and are announced in the daily papers. It may be that you will have to wait four or five years. Such luck as befell Europe in 1931, when twice in one year, on April 2 and September 26—within half a year, therefore—two total lunar eclipses were visible from beginning to end, is only reserved about once in a century for one and the same spot on Earth. But if one occurs, don't lose your chance! I have been repeatedly struck by the fact that only few people living in a town have seen a total lunar eclipse. Go and see one when you can; you will not repent it! Maybe, to see it you need not even leave your study. No entrance fee is asked. Not a single instrument is needed. The spectacle is offered to anyone who cares to see it, free!

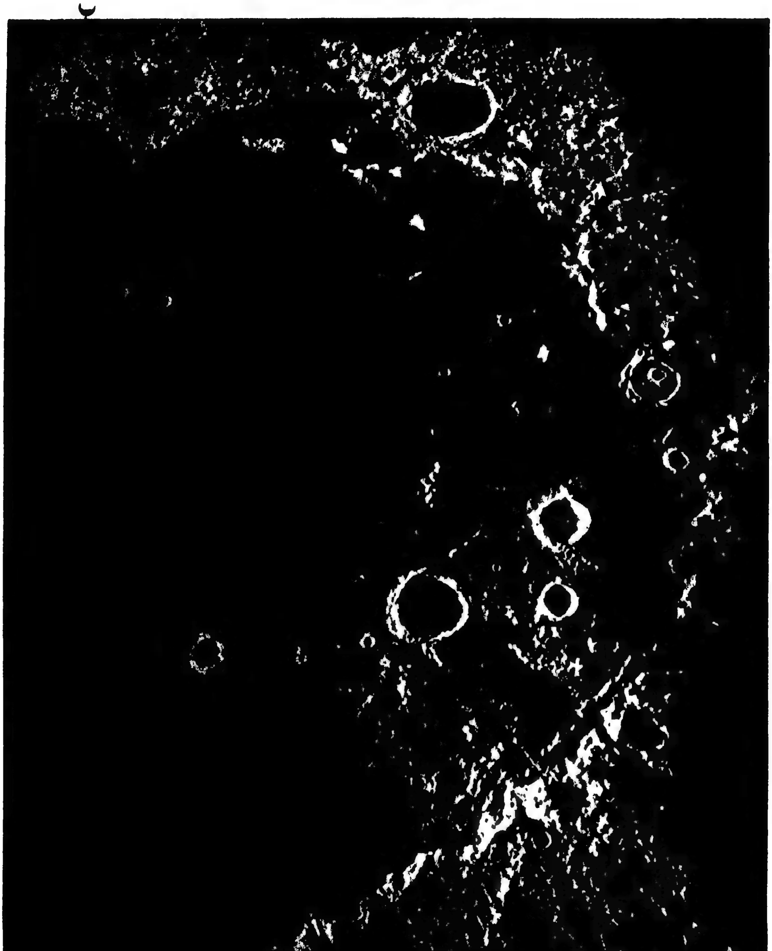
It may occur that the totally eclipsed moon is exactly "on" the horizon, while at the same moment, on the opposite side of

the horizon, the solar disk is also visible. This produces a very peculiar effect! For, as it were, we "see" the sun illuminate the moon; and yet the moon is totally eclipsed, because the sun's rays cannot reach it! The explanation is simple. There is a fairly strong refraction at the horizon, owing to which sun and moon are just visible above the horizon, while in reality they are under it. All through the year this refraction makes the days somewhat longer and the nights somewhat shorter than they would be otherwise.

CHAPTER IV

A HOLIDAY ON THE MOON

WE have decided to spend a month's holiday on the moon. But what point on the moon's surface, what country, shall we choose? The tourist agency tells us that there are plenty to choose from; no less than 59 per cent. of the moon's surface has been explored, only 41 per cent. of it has never been visible to the human eye. Perhaps this will surprise the reader, who thought that only 50 per cent. was visible. But the moon slowly shakes its wise old head or gives an almost imperceptible nod, thus occasionally showing us narrow strips left and right or above and below (this we call libration). The people at the travelling agency are even prepared to explain this fully to you. And they will, moreover, provide you with excellent moon charts and splendid aerial photographs taken from a much greater height than is possible on the Earth, and which therefore show large portions of the moon's surface. An area of about 8½ million square miles, that is, about twice the area of Europe, is open to me for my travels. Schmidt's map shows me all the details of the moon's surface: more than 33,000 different objects, seas, craters, mountains, clefts, are mapped out, the smallest no more than half a mile long. If there were any towns on the moon it would be a moment's work to find them on this map. What is it that I particularly want to go sight-seeing on my travels? The almost unbounded plains, called seas? The craters, those ring-shaped mountains, the largest of which have a diameter of from 60 to 120 miles? The mountain ranges, the highest peaks of which reach an altitude of 26,000 feet and which are, therefore, in proportion, much higher than the highest mountains on



Part of the surface of the moon: Mare Imbrium. Below: the Apennines. Near the centre: the crater Archimedes. Above it: the crater Pluto. Near the bottom left-hand corner: the crater Eratosthenes.

Photo: Mount Wilson Observatory.

Earth? The hundreds of cracks, cañons, which, a few miles wide and deep, extend in a straight line for miles and miles? Or the mysterious, pale-coloured "systems of rays," which, as in the vicinity of the mountain Tycho, extend in all directions to distances of several hundred miles? We eventually choose the area of the Apennines for our trip. The name sounds familiar and the information we are given sounds promising. The Apennines form the most important (though not the highest) range of mountains on the moon, being no less than 450 miles long. It has more than 3,000 peaks, the highest of which, the *Huygens*, rises 19,000 feet from the plain. There will be ample opportunity for climbing.

Now, having made up our minds where to go, we must attend carefully to our equipment. In the first place we must see to our complete provisions for a whole month, just as if we were going on an arctic expedition. And, worse still, we shall have to take a store of water. We shall find neither food nor water on the moon. And this is by no means all we shall have to take. On the moon there is no food, no drink, and no air either. So we shall have to take sufficient oxygen apparatus and cylinders of oxygen. We are greatly worried about what clothing to take. We shall have to endure temperatures of more than 200° Fahrenheit below freezing-point. One advantage is that we shall not have to cope with gales or storms, for there is no air, the first essential to these phenomena. But it is not only against cold that we shall have to provide, but also against scorching heat that would boil us, without proper protection; besides all this we shall have to seal ourselves hermetically from the vacuum of space. Our only resource in this matter is the special, patented moon-suit offered by the tourist agency. And then a few good blankets, which are an excellent protection against both cold and heat. We hardly need a tent—it cannot rain or snow there anyhow and there is no wind. At last all our luggage is complete and we are ready to set out.

A few days later I get out of my rocket, that has just shot me to the moon. I am wearing my patent suit; my oxygen apparatus, strapped to my back, is working, my eyes are shielded from the fierce sunlight by dark blue glasses. For I have reached the moon at full moon, the sun stands high in the heavens.

I have landed in the vast valley at the foot of the Apennines. The range of mountains stretches before me in a faintly curved line from horizon to horizon. Naturally, from the valley I can only see a small part of the range, the horizon is quite near, only a little over half as far as it is on Earth. Higher than the highest summits of the Alps, several sharp peaks point upwards. Everything is bare and rugged. Nothing but rock, waste and desolate rock. No water, no ice, no snow. The death-like silence weighs on me: not a single sound, not a whisper, not a rustle, just silence, absolute silence. There can be no sound, as there is no air and therefore no vibrations of the air. Neither is there any movement round me. If there is anything in the world that can symbolize the silence of death it must be this vast plain at the foot of the Apennines. Behind me the plain stretches grey and sullen to the near horizon. The ground is mainly covered with ash, volcanic ash. In various places there are a few somewhat larger stones of lava. So the French astronomer Lyot was right after all: his extensive research—I remember—led him to the conclusion that moonlight must be sunlight reflected by volcanic ash and stones of lava. His theory was right, and the so-fiercely-contended old idea that the lunar craters are *real* craters formed by tremendous volcanic eruptions has evidently justly been restored to favour. The ash on the ground, upon which the sun has been burning for seven days, is scorchingly hot. I brush aside some ash, until I get to the bare rock—this is icy cold, below freezing-point; the volcanic ash is a very bad conductor of heat.

I decide to mount the nearest high peak of the Apennines to get a good view of all the surroundings. I start off and

THE APENNINES AND THE CRATER ARCHIMEDES.
Photo E. Bernard.

experience—the oddest sensation of my life! I knew that it would happen, but all the same the sensation remains *equally strange. Although I weigh a good deal with all my luggage and apparatus, I feel as light as a feather.* I seem to float along. It is quite easy to jump up five yards or so from the ground, and stride a distance of twenty yards. I land just as lightly as from an ordinary jump on Earth.

Gravity is only about $\frac{1}{6}$ of what it is on Earth. The volume of the moon is about $\frac{1}{50}$, or, to be more exact, $\frac{1}{49}$ of that of the Earth. But the moon appears to be built up of substances the weight of which is on an average lighter than those of the Earth; its density compared with that of the Earth is as 61 to 100. Consequently the mass of the moon is $\frac{1}{82}$ of that of the Earth. Perhaps you will imagine that this means that its gravity must hence also be $\frac{1}{82}$ of the Earth's. But this is where you are mistaken. We already noticed that on the surface of a sphere and outside it the effect of gravitation is such as if the centre of that force were situated in the very centre of the sphere. We know, moreover, that gravitation decreases as the inverse square of the distance. On the surface of the moon we are almost four times as close to the centre as we are on Earth. Hence the effect of gravitation there is almost-four times almost-four, which is nearly fourteen times as strong as it is on Earth. The result of this is that the eighty-two times weaker force works almost fourteen times as strongly "per unit," and hence amounts to $\frac{14}{82}$, that is about $\frac{1}{6}$.

I float on over the plain. This aery tread proves to be exceedingly useful, for the volcanic ash is very soft and sandy. I soon reach the foot of the mountain range. The sides are precipitous and bare. This does not make climbing easier. But the rock is hard, unweathered and dry. There is no need to fear crumbling away of the rock, or its wearing away owing to the perpetual action of water. No loosened stones will come tumbling on to my head. My hands and feet find plenty of places to get a grip, and my body has never felt so light before. I am not troubled by mountain-sickness—I continually breathe the pure oxygen of my apparatus. It only takes me $5\frac{1}{2}$ hours to gain the summit 16,000 feet high. I sit down then at the top and survey the landscape at my ease (*see*

page 149). Again I am struck by the death-like surroundings, the silence, which, for want of any sound, can hardly be called silence. Spread out before me a vast plain, from which the Apennines steeply ascend. To the left in the plain there are some low mountains, but straight in front of me towards the North it reaches right to the horizon, 80 miles away. This horizon stands out sharply against the sky; there is no sign of any mist or haze, or any vapour at all. To the right the chain of the Apennines extends towards the horizon. On the extreme left edge of the plain the ring-shape of the Archimedes crater 120 miles away is just visible above the horizon. I hope to go there one of these days and to scale the crater edge 6,000 feet high. When I get to the top I shall be able to survey the whole crater, which is a deep plain over 50 miles from side to side. The plain before me is cleft by a crack more than 60 miles long, to the left a few miles wide, narrowing down to the right, and ending in the plain. From where I am standing it is difficult to judge the depth, but it would seem to be some miles. At right-angles to it and running between some low mountains there is a second "crack" in the direction of Archimedes. Behind me the land is very rugged and mountainous, with a few craters, and it gradually gets lower towards the horizon.

That is the aspect of the landscape at my feet. I can hardly find words, reader, to describe to you its peculiar character. And small wonder. No words of the Earth fit this lunar landscape. You will have to come and see for yourself and print the picture indelibly in your mind. You need not even leave your home to do so: take a small telescope and have a good look at the moon, at first quarter is best, when the sun's rays fall obliquely on it and throw the details into bold relief. Then you too will see the moon landscape "at your feet."

Thus far I have been so thrilled by the novelty of the landscape that I have not given more than a passing glance at the sky. I now look at it with attention, and see the

vault of heaven like a great black dome overhead and even though it is midday, and the sun is shining high up in the sky, on all sides I see the stars shining with a bright white light. There is no air here, no atmosphere such as we have on Earth that diffuses the light and gives us our blue sky. I see the stars; they shine steadily in the heavens without twinkling. As I look at this nightly sky I feel as if I am back on Earth again—I see the old familiar stars and the same constellations—their position is unchanged. The Milky Way stretches like a silver path across the inky background of sky. And look, there is Venus, to the left, not far from the sun; she is so bright that I can see her, without the aid of glasses, as a tiny little half-moon. And there is the sun, shining even more fiercely and even more dazzling than on Earth. To the left and right of the lord of day there is a strip of light, the zodiacal light (*see* page 243).

If I cover up the disk of the sun itself by holding a coin between it and my eye, I can distinctly see the corona against the black heavens!

But what has become of my good old friend the Earth? I cannot find it anywhere. But, of course, I was forgetting, naturally I cannot see it—it is full moon, and so to the moon it must be "new Earth." I remember being told this at school and yet I had not thought of it for the moment: the Earth has no light of its own any more than the moon has (even the electric lighting of our big towns does not count in world space; certainly not to the naked eye). The Earth must therefore appear in phases to the moon, just as the moon does to the Earth, but exactly the reverse: it will appear as full Earth when we see new moon, and as new Earth at full moon, as first quarter Earth at last quarter moon and *vice versa*.

It is new Earth, and the exact moment of full moon or new Earth is near. In its course from horizon to horizon, which takes nearly 15 days, the sun has almost reached its zenith. Suddenly, to its right, a black point, a strip, a

dark cap appears. An eclipse of the sun has begun. I see the sun *pass behind the Earth and disappear.* The Earth itself remains invisible, but is silhouetted black against the sun. From the faint curve on the disk of the sun, a small part of a large circle, I can easily imagine what size the Earth appears to be in the heavens, seen from the moon. The sun travels on, getting smaller and smaller to my sight. It is beginning to get quite dark and the rock around me quickly cools. The last rim of sun has disappeared, totality has set in. A large dark sphere, whose diameter is almost four times as large as the moon in our sky, is visible in the heavens, with a thin halo of reddish light round it, our Earth's atmosphere. This weird reddish light is shed on everything round me. It has now become icily cold all round and I look at my thermometer. Just before the eclipse it registered a temperature almost of boiling-point, while now it has fallen to nearly 200° Fahrenheit below freezing-point. Pettit and Nicholson, indeed, measured these temperatures during eclipses of the moon with perfect accuracy by their delicate instruments. And it was not such a simple matter for them as it is for me, who need only read off the registerings of a special thermometer. The total eclipse lasts an hour. I see little of the corona of the sun, least of all in the middle of the eclipse, the greater part of it is covered up by the Earth. When there is no eclipse, it is easier to see the corona! And what little corona light there is at the beginning and end of the eclipse is greatly outshone by the reddish light of the atmosphere of the Earth.

Now the total eclipse is over. On the right a thin crescent of sun appears, which grows and grows until, at the end of about an hour, the whole sun is uncovered in the sky. The temperature goes up again by leaps and bounds.

Now that I know exactly where the Earth is in the sky I am just able to discern it as an extremely dark grey disk against the inky black space. Hence the new Earth must,

after all, receive some light even though it is very faint. Of course, how stupid of me, the Earth now receives light from the full moon!

My climb and all the new impressions pouring in upon me have tired me. I quickly make the descent to the foot of the Apennines, lie down and fall fast asleep. I must have been terribly tired and have slept a long time. Is it that I have become adapted to conditions on the moon where day and night each last almost fifteen days? I remember waking up for a moment and realizing that the sun had gone down beyond the horizon; it was night-time and I could see the "half" Earth at first quarter in the sky. But I soon went to sleep again and had not awaked until the Earth was almost full and shining bright in the heavens. So I had slept from new until almost full Earth, almost a fortnight altogether, and yet no longer than one lunar night. Just after lunar midday I had lain down to rest and now it was about midnight.

It is icily cold all round me. The thermometer registers a temperature of about 270° Fahrenheit below freezing-point! But all my attention is taken up by the sphere of the Earth, which shines with superb brilliance overhead. It looks almost four times as big as the moon seen from the Earth. Its surface must be about fourteen times as large. What a magnificent orb in the vault of heaven! I gaze and gaze at it; then I descry a dark patch on it: an Ocean. By its shape I recognize it as the Pacific. In the North I see a white patch, the ice and snows of the North Pole—it is spring-time on Earth and I can see the North and South Poles at a time. Yes, indeed, there is the Antarctic region—I can again tell by the whiteness of its ice and snowfields Look, there is Japan, the Philippine Islands, the East Indies. There is Eastern Siberia, still under a coat of snow. And yet for all this, the image I see is not as clear as I could wish. Here and there it is vague, shadowy, broken up by spots and lines. Of course, there must be clouds over some parts that prevent me from seeing the surface of the Earth.

After watching this spectacle for some time I perceive what I have been expecting, but what is all the same a sensation at first: I see the Earth turning round on its axis from West to East. On the Eastern edge of the globe I see part of the Pacific Ocean slip round "the rim" and disappear into the Earth night; on the left edge fresh pieces become visible: there comes the Indian Ocean, India, Central Siberia, then Persia, Arabia and at last Africa, Europe. I gaze through my telescope and find England; I can just make it out on the edge of the continent of Europe.

This marvellous sight has kept me spellbound for hours. Now I see the Atlantic Ocean; in a few hours' time America will appear to my view; from here it would not have needed a Columbus to discover it!

The moment of full Earth is approaching. And then on the left rim of the Earth, in the Atlantic Ocean, at the time when day is breaking there, there appears a small round black spot, no larger than a dot, with a diameter of about 2′, so less than a fiftieth of the diameter of the disk of the Earth. It moves rapidly over the Earth to the North-East, quicker than the Earth's rotation. And now I can see well that the outline of the black spot is not distinct and sharp; to a certain distance round it the Earth is less clearly lit, rather smudged. This smudged area encircles the spot completely and measures about five times the diameter of the spot. The spot with the smudged ring round it rapidly passes over to Europe and after a few hours disappears at the Eastern edge at the moment that night falls there.

I have thus with my own eyes followed the course of a total eclipse of the sun on the Earth. I have watched the small round shadow of the moon, on which I am standing, travel over the Earth. How near it seemed, how close to one another do Earth and moon belong!

Again I fall asleep after all these excitements. When I wake up day has dawned. It is already very hot in the sun though the sun is not yet high in the heavens.

I again ascend my Apennine peak. How different the

landscape looks from when I saw it last! The mountains now throw sharp, black shadows, which completely alter the look of things. Differences in heights that I had scarcely noticed before are now clearly revealed by their sharply outlined shadows on the ground. I knew this before: I knew how distinctly the various parts of the lunar landscape, seen from the Earth, are visible at the edge of the illuminated crescent and how faint all this becomes at full moon, when the sun's rays are much less oblique or even fall at right-angles to it. Now I see the same thing from close by!

And up there I can still see the Earth almost in the same place in the sky as before. Now it is last quarter. Only the left half is visible. But yet, very, very faintly I can discern the right half, too, in this jet-black sky, on which the first quarter of the moon now sheds its pale light. I make the descent again; the end of my holiday is near; the return journey awaits me. I overhaul my rocket; all the mechanical contrivances for the start and the landing are in order—the second charge of gunpowder is intact. . . .

I am back on Earth again. I have been back for some weeks. It all seems a dream. One evening I go for a walk in the outskirts of the town. It is dark, an hour since sunset; the young crescent only three days old hangs over the Western horizon. I know from experience how lovely the light of our Earth is on the moon. And now so shortly after new moon the almost full Earth will be shining in all its glory in the lunar sky. It will be shedding its gentle light on the part of the moon not illuminated by the sun. The luminous night there is much lighter than our brightest moonlit nights. That is how it must be up there; I know it is. And again I gaze at the crescent. And then I do see the rest of the disk of the moon faintly illuminated. Faintly illuminated by the rays of the still almost full Earth.

This ashen-grey light is known as Earth-shine on the moon. We, people of the Earth, need not leave the Earth to see it shedding its light on the moon!

CHAPTER V

THE SUN

The Distance of the Sun

THE distance from the Earth to the sun is about 93 million miles. We know that this is a *mean* distance, the distance varies from 91 million to 94 million miles. This really is a considerable distance—you will remember that on the moon we were not far from home, merely a matter of some 239,000 miles. On the moon we were on an annexe of the Earth at a distance of less than 10 times the circumference of the Earth. The sun is almost 400 times as far away from us. It is hardly possible to express the distance by terrestrial standards. Imagine that we could fly to the sun in an aeroplane (which is impossible for many reasons). Travelling at a rate of about 125 miles per hour in a straight line it would take us 86 years to get there! A very long human life-time would scarcely be long enough!

Eleven thousand, six hundred and forty Earth globes placed side by side would easily fit in between us and the sun.

Determination of this Distance

The question again arises of how this distance can be determined. It is of the utmost importance to determine this distance accurately, and not merely as an answer to the question of how far we are from the sun. For, the distance from the sun to the Earth is, as it were, our standard for the whole Universe; it is an astronomical unit of length, by which the distance of the stars is measured.

We have seen how the distance from the Earth to the

moon can be quite simply determined by trigonometry (page 91). We then already observed that this method cannot be used for determining the distance of celestial bodies further away from us. So other methods must be applied. Well, these methods have been found; there are at least seven to choose from. Seven methods, which each individually produce the same result.

We shall give some of them:

1. Firstly, there is *the aberration of light* (*see* page 63). From the aberration observed the velocity of the Earth's movement in its orbit round the sun can be calculated. The length of the distance that the Earth travels in a year round the sun directly follows from this and then it is very simple to find the radius of this orbit, which is the distance from the Earth to the sun.
2. *The speed of light.*—From observations made concerning the eclipses of the moons of Jupiter (we shall say more about this later), both when the Earth is nearest to and farthest from Jupiter, it can be directly concluded how long it takes light to travel the distance of the diameter of the Earth's orbit (twice the distance from Earth to sun). Seeing that the speed of light can also be established by tests on Earth, it is quite simple to calculate the distance required.
3. It is also possible to calculate the distance to the sun by accurately studying the disturbances caused by the attractive force of the sun upon the movement of the moon, at different times.
4. Another method is by carefully studying the disturbances caused upon each other by some planets by their mutual attraction. Since the mass of these planets is known by other means, their distances to each other can be calculated from this. And from this one can find their distances to the sun and hence also the distance from the Earth to the sun.

These different methods[1] have been mentioned so as to show the reader how reliable the result obtained is, if

[1] A fifth method has been applied of late years and has even become very important: the distance from the Earth to the sun can also be measured by means of the asteroid Eros. *See* page 227.

it is invariably the same although found by such diverse calculations. We shall now have a closer look at the method that has attained the greatest fame in the history of astronomy, especially as it is quite easy to follow. It is the transit of Venus method.

Transits of Venus

The Earth is the third of the planets from the sun; Venus the second. So Venus is an inner planet, that is, its orbit lies *within* that of the Earth. It is, therefore, to be expected that from time to time it will be between us and the sun, and will therefore be visible as a very small black disk on the face of the sun: a miniature eclipse! That is indeed what happens sometimes, but seeing that the plane of Venus's orbit does not exactly correspond with the ecliptic, these transits of Venus over the face of the sun are extremely rare, on an average less than twice in a century! The last time it happened was on December 6, 1882; the next will not occur until June 7, 2004. That means that we have about another seventy years to wait!

If you look at the drawing (Fig. 22) it will be quite clear to you how we can use these transits to determine the distance of the Earth to the sun quite simply but yet very accurately. A and B are two points on Earth, as distant as possible, so a diameter of the Earth apart. The drawing shows that an observer in A will not see Venus on exactly the same point of the solar disk as an observer in B. A sees Venus in V_1, but B in V_2. Now the distance from V_1 to V_2 must be determined with the greatest possible exactitude, by both observers each determining with extreme accuracy the position in which they see Venus. The distance V_1 to V_2 proves to be about 48 seconds of arc, so less than a minute of arc, about $\frac{1}{38}$ of the diameter of the sun. It has been greatly exaggerated on the drawing so as to show it clearly.

The periods of revolution of the Earth and of Venus round the sun are known with great accuracy. According to Kepler's third law, which we shall explain later, the

ratio in which the distance of the Earth to the sun and the distance from Venus to the sun stand to each other can be derived from the ratio of these times of revolution. So we also know the exact ratio of the distance from the Earth to Venus to that of Venus to the sun. The first is to the second as 37 is to 100. By the most elementary principles of geometry it now follows that the line AB is $\frac{37}{100}$ of the distance V_1 to V_2. Thirty-seven hundredths of the 48″ found produces just over 17·6″.

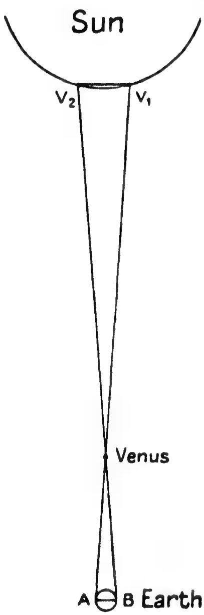


Fig. 22.

So this means that the line AB if it could be drawn on the sun would present an angle of 17·6″ from the Earth. And also that the line AB, i.e. the diameter of the Earth, would be seen from the sun at the same angle, and the radius of the Earth would appear to subtend an angle of about 8·8″.

And this gives us what we wanted. For if we know the dimensions of an object and the angle at which it is seen, it is easy to find the distance of that object. In this manner we find a distance of about 93 million miles.

The Size of the Sun

From the distance and the apparent size of the solar disk in the sky the true size of the sun directly follows. The diameter of the sun now proves to be about 864,000 miles. A hundred and nine times the diameter of the Earth! The entire orbit of the moon would find ample room to lie inside the body of the sun.

So the diameter of the sun is more than 100 times that of the Earth. From this it follows that its content (its volume) must be more than 100 times more than 100 times more than 100 times that of the Earth, so about 1,300,000 times that of the Earth. This works out to

335,300,000,000,000,000 cubic miles. That is three-hundred and thirty-five thousand, three hundred billion cubic miles. The "density" of the sun proves to be lower than that of the Earth; at least its mass proves to be only 332,000 times that of the Earth.[1]

The diameter of the sun is more than 100 times that of the Earth, of the Earth almost 4 times that of the moon. Therefore the diameter of the sun must be about 400 times that of the moon. Now the sun also happens to be 400 times the distance away from the Earth that the moon is. Hence they appear to be about the same size in the sky.

What a tremendous globe it is! The sun sends out its light and heat in all directions in the world space. Not half a milliardth part of that light and that heat ever reaches the Earth. And yet that is sufficient to make the Earth a habitable place for us humans. The sun gives us 465 thousand times as much light as the full moon, 900 million times as much as Venus and 11,400 million times as much as Sirius, the brightest star. Every square inch of the sun gives as much light as three hundred thousand candles! All heat, all light on Earth (not counting the light of the stars, negligible in this respect) is directly or indirectly due to the sun. This includes the heat of our stoves, the light of our electric lamps. For the heat of coal is only sun-heat "stored up" in the remote past; the force that gives us electric, light—whether it is produced from coal or by the force of some waterfall—is indirectly derived from the force of the sun. In a hundred ways we owe our existence to the sun.

[1] The mass of the sun therefore amounts to 332,000 × 82, or about 27 million times that of the moon. The sun is 400 times as far away as the moon; therefore its attraction upon the Earth is 27 million divided by 400^2, or about 170 times as strong as that of the moon. At first therefore it sounds strange that the tide-raising force of the moon is more than twice as great as that of the sun (*see* page 38). But the key to this puzzle is not hard to find. For the tide-raising force of a heavenly body is determined by the difference between the attraction it exerts upon drops of water on Earth that are as close as possible to that body, and its attraction upon the centre of the Earth. For the moon this difference in distance is no less than $\frac{1}{60}$, but for the sun only $\frac{1}{60 \times 400}$. So the attraction of the sun, which is 170 times as strong as that of the moon, only has a tide-raising force that (roughly) amounts to $\frac{170}{400}$ of that of the moon.

The sun is our Mother. The Earth owes its life and its being to her. The Earth is, as we shall see further on, born of the sun, just as its brothers and sisters, its fellow-planets. Like obedient children the planets, including the Earth, circle round the sun, ever accompanying her on her journey through the depths of the universe. For the sun does not stand still either; it moves with respect to the stars, carrying the whole system of planets, the solar system, with it.

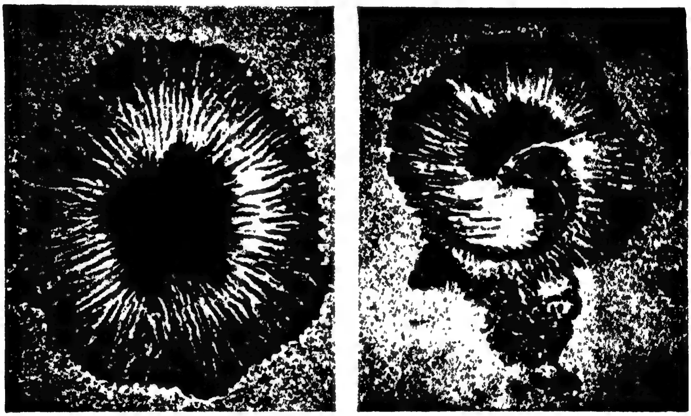
So the Earth is quite a small globe, which circles round the sun at a distance of 93 million miles. We can again make this clear by imagining a model. Let us assume the sun to be a globe with a diameter of a yard; then the Earth is a marble not quite half an inch in diameter *more than* 100 *yards away from it.* And about 10 inches away from the marble there is a tiny pellet with a diameter of about a tenth of an inch. That is our moon! Imagine these models in a large field. Think out the distances and proportions. This will give you a clear idea of the system of sun, Earth and moon. These proportions cannot be illustrated in a book, it is impossible to draw them all on the right scale; that is why drawings tend to become misleading, if this fact is not constantly kept in mind.

We all know the sun. We cannot look at it, owing to the dazzling brilliance of its light, without shielding our eyes with very dark glasses. To look at the sun without protecting one's eyes can even be *extremely dangerous!* It might cost us our eyesight. But we have all of us at one time or another attentively observed the sun, either through a thin cloud, or a light mist, or when the sun is very low on the horizon.

Is there anything to be seen on that orb that is of interest to a mere human being? Indeed there is. If we peer at the sun through a pair of ordinary field-glasses, provided with dark blue glasses, there is a fair chance that we may see something very interesting. For it is quite possible that we shall see one or more *sun-spots.*

Sun-Spots

Many a time have I seen them myself, with very small field-glasses. They consist of a dark, but not quite black, core, about the shape of a circle. Round this there is a rather uneven, lighter, grey fringe. Sometimes not more than one spot is visible, but usually they are in groups of three to five, or even more. Sometimes two spots merge into one. Very occasionally a spot, or a close group, is so large that it can be observed by the naked eye, provided it is shielded by dark glasses (or by mist). Sometimes one



Sun-Spots.

may observe the spots even without shielding the eyes, when the sun is low in the sky. It will be obvious that the spots must be very large. Very often they are larger than our Earth, they have a diameter of some tens of thousands of miles, the largest being more than 60,000 miles across.

Sun-spots appear quite suddenly on the face of the sun, but then usually stay for some weeks, sometimes for some months at a stretch. They only appear in, or near, the middle of the solar disk; you will search for them in vain near the "poles." If you were to observe them for several days, you would see that the spots drift from left to right,

that is from East to West over the surface of the sun. You can follow them for about twelve days. In the middle we see the group broadest, and narrower and narrower towards the edge: seeing that the sun is not a disk but a sphere we then of course see them lengthened out. When a group has passed from our sight on the right edge it sometimes reappears at the end of about a fortnight on the left edge. So we see that the sun rotates too, notably with a duration of about 25½ days. Unlike the moon, the sun shows itself to us on all sides.

The Eleven-year Period of the Sun-Spots

It is noteworthy that the frequency of the occurrence of sun-spots is *periodical*; that is to say, the number of sun-spots decreases during a period of a certain length, and then increases again during a certain period. Every eleven years there is a minimum, and every eleven years there is also a maximum. After the occurrence of a minimum the number of spots increases for about 3½ years, then it decreases again for about 7½ years. This period of 11 years is not inalterable, sometimes it is longer, sometimes shorter; but the average is 11 years. The difference between the number of spots at a maximum and at a minimum is very great; thus during the maximum of 1883 no less than 1,155 spots were observed in a year; during the minimum of 1889, only 78; in the maximum of 1893, 1,464, and in the minimum of 1901, 29. So you see that you will stand a much better chance of finding a spot during the maximum than during the minimum.

Astrophysics

In spite of the many attempts to explain them, sun-spots are still an astronomical puzzle. Nor is the cause of the periodicity of their occurrence known. As regards this, it can only be said that during a sun-spot maximum the entire solar activity is stronger and more violent, and this is reflected in other phenomena, as we shall see later. Why

it is that this activity fluctuates is not known, however, although of late years some insight has been gained into this problem. Astrophysics, star physics, is a young branch of astronomical science. This branch of science deals with the physical and chemical processes at work upon the surface of, and inside, the stars (our sun being also a star), and endeavours to explain those processes in terms of terrestrial physics. But the difficulties of this new science are not to be underrated. Although we shall soon learn that the materials that go to build up the stars are the same as occur here on Earth, yet it must be borne in mind how widely physical conditions on the stars differ from those here on Earth! In our laboratories we cannot possibly imitate conditions prevailing on the sun and the stars. To begin with, it is impossible to reach the temperatures prevailing on the surface of all but the coolest stars, the temperatures of the hotter surfaces attaining tens of thousands of degrees. We cannot even approach anywhere near the temperatures that are believed to occur inside the stars according to physical calculations, namely temperatures about ten million degrees centigrade. Again, inside the stars there is a very high pressure which we cannot reproduce in the laboratory. What will be the behaviour of a substance at a pressure and a temperature a thousand times, ten thousand times, as high as we can achieve in our laboratories?

Up to a few years ago it would have been audacious to attempt to give an answer to these questions. But the progress of science is rapid. And the remarkable thing about it is that the key to the very greatest is perhaps to be found in the very smallest. The science of the atom was born during the last three or four decades. Half a century ago the atom was regarded as the very smallest particle of matter—the name itself means "not divisible." *Trillions of such atoms are present in one pin-head.* It is now known, however, that the atoms of the 92 elements known to science are built up of still smaller particles, and that, within certain limits, they can be regarded as minute solar systems, in

which extremely small particles (electrons) revolve round the nucleus. In the case of the lightest element of all (hydrogen) only one electron revolves round the nucleus; in heavier substances the number of electrons is greater, up to 92. Of recent times successful attempts have been made to obtain some knowledge about the nucleus. This in its turn proves to consist of several constituents, protons and neutrons; The protons are positively charged, the electrons negatively; the neutrons have no electric charge. The nucleus of hydrogen only consists of one single proton.[1] In every atom, at least in its normal state, the number of protons and electrons is equal. But however interesting this may be, it would lead us too far from our subject to discuss it here.[2]

This insight into the most minute structure of matter helps us to understand what goes on in the stars. It enables us to realize that the state of an atom, which in itself consists of a whole system of nucleus and electrons, at such a totally different pressure and temperature as prevails inside a star, can be completely different from what it is on Earth. It is generally supposed that there the complete atom is shattered, and, like a watch hit by a hammer, is destroyed beyond recognition. Or, to put it differently, that *our* form of atom, with the physical phenomena that attend it, does not exist, cannot exist, inside any of the stars. It is possible that in those stars a phenomenon occurs, continuously and on a large scale, which we know on Earth only in the form of "radioactivity" in some heavy elements (although it appears to be possible to generate it artificially in other elements): *the conversion of matter into energy.* This would also be an explanation of the almost inexhaustible source of light and heat of the sun and stars.

Science nowadays knows in what direction it has to seek

[1] The composition of the nucleus of what is known as "heavy" hydrogen, recently discovered, is less simple.

[2] The new science of the atom progresses with amazing rapidity. Important new discoveries have been made and are made nearly every day. Thus, for instance, new particles have been discovered: the above-mentioned "neutrons" (with no electric charge) and "positrons" (electrons with a positive charge).

to unravel the mystery of the processes occurring on the sun and stars. Much has already been found in this way of recent years, and it is felt that we are on the threshold of certain, definite knowledge. A closer study of what are known as "cosmic rays," which would appear to owe their existence to these atomic processes in the stars, would seem to hold out promise of reward. This is the object of the ascents by balloon made nowadays into the stratosphere, where these cosmic rays can best be examined. Before many years have passed science will in all probability have lifted the veil from the secret of these cosmic rays. At present many points are uncertain.

The reader will now be aware of the great difficulties attending an exact understanding of solar activity and will no longer be surprised at the absence of an explanation of the eleven-year period of the sun-spots.

Strange to say, this eleven-year period can be observed in various terrestrial phenomena. Thus the magnetic needle of the compass, which points to the North, shows slight daily oscillations. Now these oscillations are much more pronounced during a sun-spot maximum than during a minimum. The number of sun-spots definitely corresponds with the extent of the oscillation of the needle of the compass.

The same relationship is shown by the Northern Lights or *Aurora Borealis.* This is an electric phenomenon that happens in the very highest, most rarefied strata of our atmosphere. This phenomenon is much more frequent during a sun-spot maximum than during a minimum.

Indeed, the relationship between sun-spots on the one hand and Northern Lights and the compass needle on the other is even closer than the above would lead one to suppose. When suddenly a particularly large spot makes its appearance on the sun, then, within a few hours, the needle of the compass is disturbed on Earth: what is known as a "magnetic storm" then occurs. Moreover, there is then every chance that a particularly fine occurrence of Northern Lights will

happen at the same time, which may even be visible in our latitudes. (Northern Lights may be seen in our country several times a year by a watchful observer far away from our towns.)

It is really a most remarkable thing that the occurrence of sun-spots is attended by such phenomena on Earth. When the true nature of these spots is known this relationship will no doubt become less puzzling.

Attempts have often been made to find in weather conditions an eleven-year period which is supposed to be connected with the intenser activity of the sun. Periods of good harvests and bad would then vary every eleven years. The economist Stanley Jevons even tried to find in the periods of the sun-spots an explanation of the periodical economic crises—*via* the harvests! No direct effect upon the weather by the sun-spot period has ever been proved with certainty, although it would by no means be surprising if the increased intensity of the solar activity should have some influence upon our atmosphere. In this connection it is worth mentioning that the celebrated winter period believed to have been found for the winters in Western Europe by the Dutchman Easton, consists of four parts, each of twice eleven years.

Corona and Prominences

Is there anything else for a mere human to observe on the sun? Indeed there is, but only under the very special conditions of a total eclipse. We already referred to the corona, the halo round the sun. This can be regarded as a kind of high solar atmosphere. Occasionally, however, during a total eclipse, one can see with the naked eye even, but better still through a telescope, behind the dark rim of the moon, prominences flashing up from the edge of the sun, immense tongues of flame, sometimes of a reddish hue. It has even been proved possible to observe these prominences without there being an eclipse. It appears that these prominences rise tens of thousands of miles, sometimes more than a hundred thousand miles, from the surface of

the sun. In the space of a few hours they can mount to this terrific height. The number of prominences proves to be highest during a sun-spot maximum, when the solar activity is most intense.

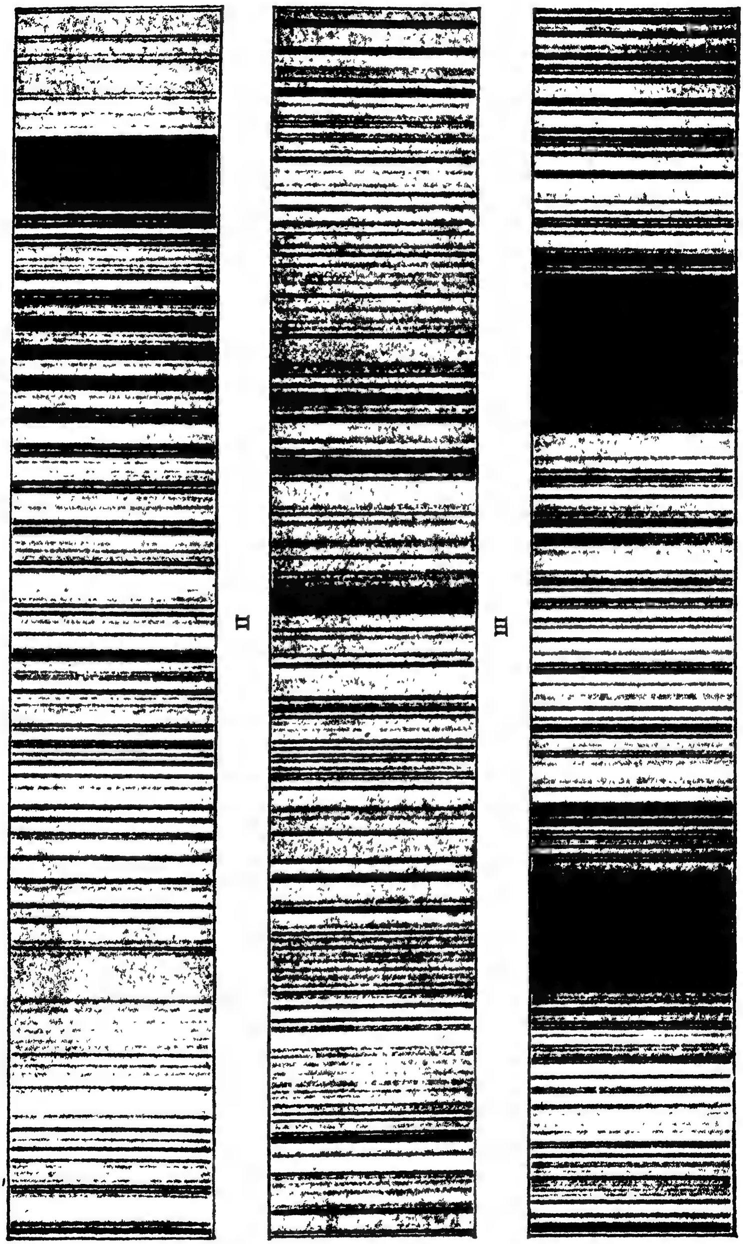
What must we imagine the sun to be? It is obvious that at the temperature of the sun's surface, which is about 10,000° F., neither solids nor liquids can exist. We pass over the question of what is inside the sun, for the moment. At the surface any substance, whatever it is, must be in a gaseous state. So our sun and all the stars are therefore encircled by an atmosphere of gases, where the constituents of which its outer layers are built up, the elements which we here on Earth know normally in a gaseous, liquid or solid state, all occur in a gaseous state. At the surface of the sun, therefore, iron, copper and other metals are gases, just as here on Earth are oxygen, nitrogen, argon, and so on. The solar atmosphere and the atmosphere of the stars consist of mixtures of all these gases. At the surface of the stars and the sun conditions of temperature and pressure are not *so* exceptional, not *so* different from those on Earth, as to make any great difference in the structure of the atom. That it is a different matter inside the stars is obvious from the foregoing.

Spectral Analysis

The interior of the sun, then, is the immense laboratory, the vast workshop, where the energy that flows into the world space as light, is generated. Before this light, of the sun or the stars, altogether leaves the heavenly body, it must first penetrate through the relatively much cooler atmosphere of gases round the heavenly body. Now when, in our laboratories on Earth too, light penetrates through a cooler gas, certain rays of the light are withheld by the gas, they are *absorbed*. And they are the very rays produced by the gas itself when made luminous, as, for instance, in a Geissler tube. White light consists of rays of various wavelengths; if it falls through a prism or through raindrops,

it is broken up; the rays of diverse wave-lengths, which make the impression of different colours on our eyes, are then spread out side by side in a kind of ribbon. This ribbon is called the spectrum. If we carefully examine the spectrum of a white slit-shaped source of light, after the light has passed through cold hydrogen, this spectrum proves to be broken up in several places (absorption spectrum). We see dark lines of perfectly specific wave-length, which are peculiar to hydrogen, and to hydrogen only, not occurring in any other substance, in any other element. They are the same lines as are emitted by glowing hydrogen as bright lines after its light has fallen through a slit and has been spread out by a prism (emission spectrum). Why these particular lines appear in the spectrum or, in other words, why rays of this wave-length are emitted by one special element, has been fully explained of late years by the research into the structure of the different atoms. The position of the different lines can, theoretically, be accurately calculated, and the calculated positions tally exactly with those actually found. It has even happened that new lines were discovered in theory first and then found in the laboratory afterwards!

Every substance, every element, thus has its own characteristic lines in the spectrum. This can be observed by means of an instrument called a spectroscope. The lines are called Frauenhofer lines after their discoverer. The spectra of sun and stars are photographed by a combination of telescope, spectroscope and camera. Then such a photograph can be studied with care and the place of the lines determined under a microscope. We look at such a photo in the same spirit as at that of a group of people; we first have a good look at the faces to see if we can find anyone we know; the photograph of the solar spectrum or of the star-spectra is scanned for lines in a familiar position, thus finding what substances, what elements, occur on the sun or star. For we know the characteristic lines of each known element by our research: their place in the spectrum was carefully determined long since. If now in these spectra



PARTS OF THE SPECTRUM OF THE SUN.

we only find lines we know, the conclusion is obvious and of the very utmost importance: it means that *on the sun and the stars no other elements occur than may be found here on Earth. All heavenly bodies are built up of the same materials—the Universe displays distinct uniformity in structure.* A uniformity which leads us to the conclusion that all constituents of the Universe have a common origin.

It proved to be the case. When in the middle of the nineteenth century this new method of research—spectral analysis—was discovered, it appeared that the spectra of the sun and the stars only contained known lines. So the heavenly bodies only contained terrestrial elements.

There proved to be one exception. Certain lines in the solar spectrum did not correspond with those of any known terrestrial element. *So a new element was discovered in the sun.* This was called helium from the Greek word meaning sun. But then it transpired that it did exist on Earth after all; the famous British physicist Ramsay was able to prove its existence on Earth in 1894. Our ordinary everyday air, a mixture of nitrogen, oxygen, argon and small quantities of other gases, also appeared to contain a vestige of helium. The spectrum of the element discovered by Ramsay distinctly showed the same lines. In later years helium was found to occur in slightly larger quantities in some natural gases, so that nowadays it is even used for filling airships. It has slightly less lift than hydrogen (nearly ten per cent.) but does not burn, so is much safer to use.

It was first thought that there were a few other new elements in the spectra of the stars not existing on Earth, but it has transpired since that they are after all elements known to science, but which have undergone a slight change in the structure of their electrons. So here it was not a fresh person on the photograph but a familiar friend in disguise.

In addition we must not forget to point out that the study of the spectra has become a rich source of new knowledge for astronomy in other respects. All kinds of other facts, such as velocity, luminosity, exceptional density and

even rate of rotation of a heavenly body can be derived from the spectrum. We shall say more on this subject later on.

Spectral analysis has now taught us that the sun and the stars contain the same elements as the Earth. The Earth resembles the sun. But is that then anything to be surprised at in a daughter of the sun? And both the sun and the stars will also prove to be members of one large family, the Milky Way family.

But let us not look too far ahead. We must first keep to the sun.

By means of our model we have seen exactly how the sun displays itself to different places on Earth on different days of the year. But we must now draw your attention to another aspect of the same matter.

The Zodiac

Seen from the Earth the sun always appears in the plane of the ecliptic. It could not be otherwise: it follows from the definition of that plane; if, in my model room, I put the sun in the middle of the floor and the Earth travels along an orbit drawn in the floor, then from the Earth I naturally see the sun in the plane of the floor, and therefore in the ecliptic (a difference in position on the Earth can only make a difference of a few seconds of arc). If I imagine the floor of my room to be produced infinitely, the floor bisects the whole world space into two parts. If I imagine a vault of heaven such as the firmament appears to form to my vision, then my floor will bisect that vault. That section must appear to inhabitants of the Earth as a circle in the dome of heaven. To put it differently: my floor, the ecliptic, produced infinitely, touches stars and constellations that lie in the produced line of the ecliptic. To the vision of an inhabitant of the Earth the sun will appear to travel along these constellations in the course of a year, in a year it will "pass along the ecliptic through the heavens." Constellations are groups of stars, strung together more or less at random by man; seen from the Earth the members of each constellation

are in each other's vicinity. Anyhow, the path that the sun appears to follow through the firmament, the ecliptic in the heavens, has been divided into twelve constellations, in each of which the sun appears to stay for a month. These are the twelve constellations of the zodiac, the Signs of the Zodiac: Aries, Taurus, Gemini, Cancer, Leo, Virgo, Libra, Scorpio, Sagittarius, Capricornus, Aquarius, Pisces, which mean: Ram, Bull, Twins, Crab, Lion, Virgin, Scales, Scorpion, Archer, Goat, Waterman, Fishes.

Astrology

So in a certain month of the year the sun is in the sign of Cancer. In olden times, when people were ignorant of the fundamental principles of astronomy and not aware of the smallness of the Earth in the whole scheme of the Universe, this fact was held to be of great importance, and from the position of the sun, the moon and the planets (as far as they were known in those days) at the moment of a person's birth they divined the course of one's future life. It has never been quite clear why they took the moment of birth and not the moment of conception. To anyone with an open mind it cannot possibly have any influence on a person's after life or character whether the actual birth is some days or weeks earlier, say by medical necessity.

But even apart from this, astrology is a doctrine at which we must look askance with our present knowledge of the heavenly bodies. It is no good arguing about it. Reason has no more to do with astrology than it has with fortune-telling from cards or any other means. It is really a mystery how otherwise very sensible people can still believe in it.

So the sun is in a different sign of the zodiac every month; in the same constellation for a certain month every year. However, owing to the precession of the equinoxes (*see* page 80) this rule does not hold good for ever. Our seasons, our calendar months travel through the whole orbit of the Earth in about twenty-six thousand years; in other words through the whole zodiac, so one twelfth of

that distance in upwards of two thousand years. Therefore, since the days of the ancient Greeks, the sun in a certain month has dropped behind one constellation in the zodiac, and is in the same constellation a month later. But astrologists as a rule simply ignore this; for them the sun is in a certain month in exactly the same "sign" as it was many centuries ago!

CHAPTER VI

THE PLANETS—THE SOLAR SYSTEM

General Structure of the Planetary System

In the preceding pages we have several times referred to our Earth as a planet, and to our sisters and brothers the other planets. They are all of them children of our Mother, the sun. They all revolve round their Mother in orbits, which are almost circles. We are now going to become better acquainted with this whole family.

Starting from the sun we first reach *Mercury*, at a distance of about 36 million miles from the sun; it makes one complete revolution round the sun in 88 days. The diameter of Mercury is about 3,000 miles, so not very much more than that of our moon. Except perhaps for *Pluto*, it is the smallest of the major planets. (We shall deal with the minor planets, the asteroids, later on.)

After Mercury we come to *Venus*, at a distance of 67 million miles from the sun. The period that Venus takes to travel round the sun is 224½ days. Its diameter is 7,800 miles, little less than that of the Earth.

The third planet is our own *Earth*, which, as we know, revolves round the sun at a distance of 93 million miles in one year. The diameter of the Earth is 7,922 miles.

Next comes *Mars*, at a distance of 141 million miles from the sun. The period of Mars is 687 days, that is to say almost two years. Except for Mercury (and presumably Pluto) Mars is the smallest of the planets; it has a diameter of 4,200 miles.

After Mars comes *Jupiter*, 483 million miles from the sun. Its period is almost twelve years. Jupiter is the

giant among the planets; it has a diameter of no less than 87,000 miles which is more than ten times that of the Earth.

We next come to *Saturn*, the famous ringed planet. Saturn is 886 million miles from the sun and takes 29½ years to revolve round it. Saturn is another very huge planet, the next largest after Jupiter and not much smaller. Its diameter is about 74,000 miles.

After Saturn we get *Uranus* (this planet and those following were not discovered till modern times). Uranus is at a distance of about 1,800 million miles from the sun and has a period of 84 years. Its diameter is 31,000 miles.

We then come to *Neptune*, the planet which up to recent times was considered to be the last. Neptune, celebrated by the story of its discovery, is 2,800 million miles from the sun and has a period of 164½ years. Its diameter is 33,000 miles.

Last of all comes *Pluto*, a recent discovery, of which we do not yet know all the elements. The distance from Pluto to the sun, which greatly varies from perihelion to aphelion, is on an average about 3,700 million miles. Its period is about 248 years. The diameter of Pluto has not yet been determined for certain. It is certainly smaller, and in all probability considerably smaller, than that of the Earth.

To sum matters up clearly, here is a *Tableau de la troupe* once again:

	Mean distance to sun	*Period of revolution*	*Diameter*
Mercury .	36 million miles	88 days	3,000 miles
Venus .	67 ,, ,,	224½ ,,	7,800 ,,
Earth .	93 ,, ,,	1 year	7,922 ,,
Mars .	141 ,, ,,	687 days	4,200 ,,
Jupiter .	483 ,, ,,	almost 12 years	87,000 ,,
Saturn .	886 ,, ,,	29½ ,,	74,000 ,,
Uranus .	1,800 ,, ,,	84 ,,	31,000 ,,
Neptune .	2,800 ,, ,,	164½ ,,	33,000 ,,
Pluto .	3,700 ,, ,,	248 ,,	3,000 ,,

A distance such as that of Pluto really amounts to a good deal, even speaking in terms of world space. An aeroplane would need about 3,500 years to make the journey. At the present state of our knowledge, we are now at the end of our solar system and so—really quite near home. Indeed, we can even maintain, we are still inside our own dwelling! To reach the *nearest* star, we should have to travel 6,000 times as far again!

It is a good way to get an idea of the proportions of our solar system by again resorting to a model. We again take the sun to be a globe with a diameter of one yard. At this ratio Mercury is a pea at a distance of 40 yards, Venus a cherry 75 yards from the sun, the Earth a cherry at 100 yards, Mars a large pea at 165 yards, Jupiter an orange at 580 yards, Saturn a small orange at 1,100 yards, Uranus a plum at 2,100 yards, Neptune a plum at 3,300 yards, Pluto a pea (?) at about 4,500 yards.

This will serve to give you an idea of the almost alarming emptiness of the Universe. Nearly everywhere there is *nihility*; dotted about here and there at immense intervals minute specks sail about. If we wished to include the nearest star in our model there would be no room on Earth to give it its proper place. For if we are to keep the right proportions it would have to be 17,000 miles away from our sun with a diameter of one yard. It is nearly impossible to conceive such emptiness!

So this is how the nine major planets circle in their orbits round the sun. We shall now have to take a closer look at these orbits. Then it at once becomes evident that great unity and order prevail in the solar system. The orbits of the planets are, generally speaking, practically circles; all planets move more or less in the same plane; the inclination to the ecliptic of the planes of the orbits is but slight: Mercury 7°, Venus 3½°, Mars 2°, Jupiter 1°, Saturn 2½°, Uranus 1°, Neptune 2°, Pluto 17°; all planets travel about the sun in the same direction, which is also the same direction

as the rotation of the sun on its axis. We may notice from the above that the further away a planet is from the sun, the longer it takes to complete its orbit.

Kepler's Laws

The question that now rises is whether there are any other rules in existence which the planets obey, whether there are physical laws which their orbits are in accordance with. And the answer is that indeed there are. There are three, called Kepler's laws after their discoverer, who lived from 1571 to 1630.

The first law is: *The orbit of each planet is an ellipse, having the sun in one of its foci.*

We saw that the path of the Earth round the sun is not exactly a circle. If it were a true circle the Earth would always be equally distant from the sun. This proved not to be the case: during the first days of January the Earth proved to be nearer the sun than it is in the beginning of July.

So Kepler found out that the orbits of the planets are ellipses. You can make an ellipse in the following simple way, a way often applied by gardeners when they want to lay out a nicely oval flower-bed. They drive two pegs into the soil at a certain distance from each other. Now they wish to trace the shape of their flower-bed in the soil with a stick. How can they do this? They take a length of string and tie the ends together, thus making it "endless." This is placed round the two pegs in the ground. Now the gardener draws the string taut round the pegs with the stick, so that it forms a triangle on the ground with the two pegs and the stick in its corners. Now if he slides the stick over the soil keeping the string quite taut, he will draw an *ellipse* on the ground. The further the pegs are away from each other the more elongated the ellipse will be; the closer they stand together, the less will be the *eccentricity* of the ellipse, and the more it will resemble a circle. If the two pegs are on one spot the ellipse becomes a pure circle. The eccen-

tricity is then 0. The two pegs are the foci of the ellipse. The stick is the planet.

The eccentricity is equal to the distance of a focus to the centre, divided by half the "long axis." It is obvious what is here meant by the centre and by the long axis. (Fig. 23.) Such are the ellipses described round the sun by the planets. The sun is in one of the foci. Seeing that the deviation of the planets' orbits from a circle is generally very slight, these orbits may be regarded as circles when

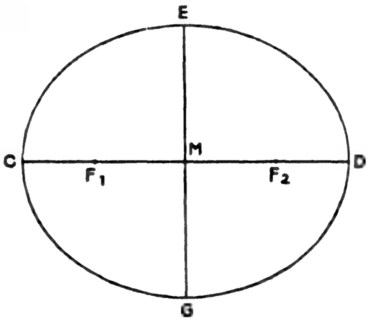


Fig. 23.
F_1 and F_2 = Foci
M = Centre
CD = Long axis
EG = Short axis
CM = MD = Half long axis
$\frac{MF_1}{MD} = \frac{MF_2}{MC}$ = Eccentricity (in this Fig. 0·55).

determining their "behaviour," as long as great exactitude is not a requirement. (Fig. 24.)

The eccentricity of the Earth's orbit is over $\frac{1}{60}$, that of Venus only $\frac{1}{150}$, of Neptune under $\frac{1}{100}$, of Jupiter almost $\frac{1}{20}$, of Mars just over $\frac{1}{11}$, of Mercury more than $\frac{1}{5}$ and of Pluto $\frac{1}{4}$.

The second law of Kepler says that: *The motion of each planet in its orbit is such that equal sectors are described in equal times.* We noticed before that the Earth travels faster as it is nearer the sun in its orbit. This is also the case with other planets. The greater the eccentricity of a planet's orbit is, the greater will be the difference in the rate of revolution of the planet in the various parts of its orbit.

Kepler found the simple law by which relationship is established between the distance to the sun and the speed of

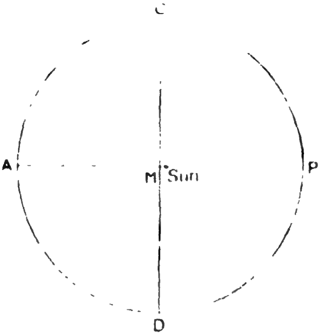


Fig. 24.

The ellipse described by the Earth round the sun, drawn in the correct proportions

Eccentricity $= \frac{MS}{MP} = \frac{1}{60}$

P—Perihelion
A—Aphelion.
MP = MA = 60 = half long axis
MS = 1.
MD = MC = half short axis = 59.99
SP = 59.
SA = 61

Seeing that MP = MA = 60 and MC = MD = 59.99, by far the easiest way to construct the ellipse of the Earth's orbit in correct proportion is by drawing a circle with M as the centre and a radius of 60 millimetres. The error then made is less than a hundredth millimetre

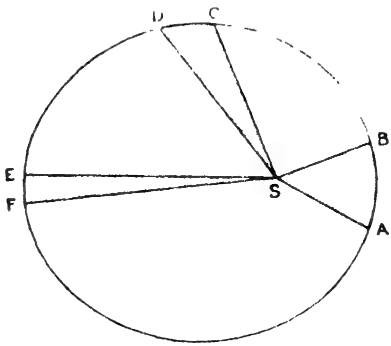


Fig. 25.

KEPLER'S SECOND LAW.

The areas of the sectors SAB, SCD and SEF are equal. The planet proves to travel the distances AB, CD and EF in equal times.

the planet in its orbit. Fig. 25 will make this point clear. The planet travels the distance AB when it is close to the sun,

say in a month's time; when it is farther away from the sun, the distance CD in the same time, and if it is farther still away from the sun, the distance EF. Now the second law says that the areas of the sectors SAB, SCD and SEF are equal.

The third law of Kepler is perhaps the most remarkable and reveals a wonderful regularity in the motions of the planetary system. We showed above that the periods of revolution of the planets are longer as they are farther from the sun. Now Kepler discovered a simple mathematical relation between these two factors. *The squares of the periods in which the planets describe their orbits are proportional to the cubes of their mean distances from the sun.*

We shall explain the purpose of this by some examples. The distance from the sun to the Earth is what we shall call for the sake of simplicity, 1, and the period in which the Earth describes its orbit round the sun is one year. Let us take a planet at a distance four times as far, so at a distance of 4. The cubes of these distances are related to each other as $1 \times 1 \times 1$ to $4 \times 4 \times 4$, i.e. as 1 to 64. To find out how the periods of these two planets are related, we apply Kepler's third law, which says that the squares of their periods of revolution are related as the cubes of their distances to the sun. For this relation we found in our example of the planet that is four times the distance from the sun that the Earth is, 64 : 1. We must now find of what number 64 is the square, that is, what number must be multiplied by itself to get 64. This is 8. In mathematics, we say 8 is the square root of 64 ($8 = \sqrt[2]{64}$). Therefore the planet that is four times the distance from the sun that we are, will take eight times as long to complete its circuit round the sun.

If we take other figures for our example the sum becomes more involved. Let us take a different planet, ten times as far away from the sun as the Earth. Then the relation of the cubes of the distances is $10 \times 10 \times 10$ to $1 \times 1 \times 1$, or as 1,000 to 1. Now we must find what number multiplied by itself produces 1,000. There is no whole number that will fit in here; but that does not matter much. 31 times

31 is 961; 32 times 32 is 1,024. The number we want is between 31 and 32 and must therefore be about $31\frac{1}{2}$. We need hardly tell our readers that there is a simple method by which the square root of 1,000 can be calculated with exactitude. The above rough method will serve our purpose. The planet that is ten times as far from the sun as the Earth is will describe its orbit in $31\frac{1}{2}$ years.

And now we shall see how this theory fits in with fact:

Planet	*Distance*	*Time required to describe orbit*	*Square of period of orbit*	*Cube of the distance*
Mercury	0·387	0·241	0·0581	0·0580
Venus	0·723	0·615	0·3785	0·3779
Earth	1	1	1	1
Mars	1·5237	1·881	3·538	3·538
Jupiter	5·2028	11·862	140·7	140·8
Saturn	9·539	29·458	867·8	868·0

You will see that the figures tally well, the differences are very slight. We shall see later on why there must be minute differences, why Kepler's third law cannot be quite exact. But for as far as we have got now it is sufficiently accurate.

So the time that a planet requires to complete its orbit round the sun increases rapidly as the planet is at a farther distance from it. If the distance from a planet to the sun is four times as long as that of another planet then the orbit of the former will be four times as long. The lengths of the orbits are related as the distances to the sun. If therefore both planets travelled with an equal velocity, the planet four times the distance away from the sun would require four times as much time to complete the circuit once. We saw, however, that it requires eight times as long. Therefore it travels at half the rate. For a planet ten times as far away we found that it requires about $31\frac{1}{2}$ times as long to complete one circuit round the sun. So it travels at not quite the speed of the first planet. A planet at 100 times the

distance is found to need 1,000 times the time, so it travels one-tenth of the rate of the first planet.

The farther the planets are from the sun, the more slowly they travel in their orbits. And could we really expect anything else, after learning something about the effect of universal gravitation, about the relation between fall and revolution, and after becoming acquainted with Newton's universal law? Kepler lived before Newton, however. It was left to Newton to show how Kepler's three laws could easily be derived from his universal law of gravitation. We shall not repeat here how that is done.

As regards Kepler's third law, we shall just show how it can be derived from Newton's general law. We again take the example of two planets one of which is four times the distance from the sun that the other is. Let us call the nearer planet 1 and the farther 2. If now planet 1 and planet 2 described their orbits about the sun in the same time, then, in a given time, say 4 seconds, planet 2 would travel the same part of its orbit (say, a millionth part) as planet 1 in its orbit. But seeing that the whole orbit of planet 2 is four times as long as that of planet 1, the part of the orbit that 2 travels in four seconds would be four times that of planet 1. Because in the case of these two planets all proportions are as 4 to 1, the "fall" of planet 2 towards the sun in these four seconds, in Newton's sense, would also be four times that of planet 1. But that would be contradictory to Newton's general law: a planet four times as far away does not "fall" four times as far in the same time; on the contrary, much less. According to Newton's law the force of gravitation decreases with the square of the distance, and planet 2 therefore "falls" only one-sixteenth of the "fall" of planet 1. So if we assume an equal period of revolution for both planets, planet 2 would "fall" 64 times too much.

So it is certain that it must have travelled a much shorter distance in four seconds, in fact so much shorter that the height it "falls" is only $\frac{1}{64}$. So the problem is reduced to the query: By how much must the distance be reduced to reduce the height the planet "falls" to one sixty-fourth? Well, just look at the drawing (Fig. 26). Planet 2 travels from A to B. At B the "height of fall" was DB. This was 64 times too much. Now let us take point C half-way between A and B. What length will the distance of "fall" EC be there? It must be remembered that in our example we are concerned with minute distances. The

angle BSA is therefore extremely small too. Well, with such small angles, CE = $\frac{1}{4}$ of BD[1] if C is half-way between A and B. If we again halve the distance AC, the distance of "fall" is again reduced to a quarter. This brings us to $\frac{1}{16}$. And if we again divide by two we have reached $\frac{1}{64}$ of the original value. So the exact distance of "fall" corresponds with a distance covered of $\frac{1}{8}$ of the original. From this it directly follows that planet 2 describes its orbit in eight times as long a time as planet 1. And that is exactly what must be the case according to Kepler's third law.

So the universal law of gravitation is found to govern the revolution of the planets, and from this law Kepler's laws, which establish certain properties of the planetary orbits, can be derived. It immediately follows from gravitational attraction, however, that Kepler's laws cannot apply

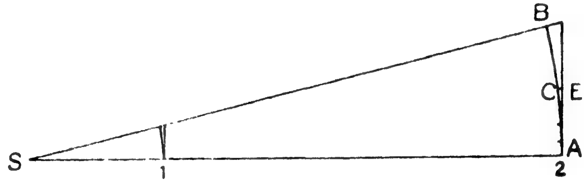


Fig. 26.
KEPLER'S THIRD LAW.

accurately to a fraction, but that they can only be approximate laws. For we must not forget that not only does the sun attract the planet, but the planet also attracts the sun. It is only because the planet is so small in comparison to the sun and its influence hence almost negligible, that Kepler's laws are so in keeping with actual facts. In reality, however, the planet does not revolve round the centre of the sun, but round the common centre of gravity of the sun and the planet, which is certainly very close to the real centre of the sun, but not exactly in it. So Kepler's laws follow from

[1] If we lay the "plane of horizon" at a given point on Earth, this plane, for exactly the same reason, at a distance of 12 miles does not lie twice as high, but four times as high above the surface of the Earth as it does at a distance of six miles. This rule only applies, as we have already said above, if the distances and angles are comparatively small. The approximate formula: BD = AB^2 divided by the diameter of the planet's orbit and CE = AC^2 divided by that same diameter, tallies with actual fact, if the angles are small and especially if they are very small. So if AC = $\frac{1}{2}$AB, CE = $\frac{1}{4}$BD.

Newton's theory of gravitational attraction, but it also *follows from this theory* that Kepler's laws cannot be *perfectly exact. Which* we had already seen *in the figures above.*

Position of the Planets

We now know something about the actual orbits of the planets and the forces that move them. But now the question arises of how we see these planets *from the Earth* in the vault of heaven. We stated that the orbits of the planets are at a very small angle to the plane of the Earth's orbit round the sun, so that the planets are always found in the sky near the ecliptic. Only Mercury, Venus, Mars, Jupiter and Saturn can be seen with the naked eye. Uranus can only be observed occasionally under very favourable circumstances, if you have strong eyes, as a faint little star; Neptune can only be seen through a telescope, and of course Pluto can only be found through the very strongest telescopes. By people in our part of the world Mercury is seldom seen.

But Venus, Mars, Jupiter and Saturn are brilliant "stars" in the sky. So we must look for them in the ecliptic. But in what part of the ecliptic? What orbits do we see them describe in the ecliptic?

Before we answer this question we must first settle another which will give us a clue to the first, i.e. how do we determine the place of the ecliptic in the sky? We know that this place is indicated by the constellations of the zodiac. If we know them, we are on the right track. If we do not, we must try to find our way by means of an astronomical chart. If we have not got that either, we must again resort to our model room.

There we can find the answer to many questions. We see there that in a certain place, say London, the plane of the horizon always behaves in the same way with respect to the ecliptic during a rotation of the Earth, at any time of the year. During every rotation at a certain moment the angle of inclination is large, about 61½°, then it diminishes, until, at the end of twelve hours,

it is at its smallest, about 14½°, then, in another twelve hours, it again grows to 61½°. This happens during any part of the year. The revolution of the Earth round the sun has no effect upon this whatever, as we may see in our model room. But this revolution has the greatest possible effect upon the question as to at what hours of the day these various positions of the plane of the horizon with regard to the ecliptic occur, or—to put it differently—of the ecliptic with respect to the plane of the horizon. As we know, the ecliptic is, in our country, *high in the heavens at midday in summer, low in the sky at midnight in summer, low in the sky at noon in winter, high in the sky at midnight in winter.* Now we can add to this:

The ecliptic is high at the vernal equinox (March 21) at sunset, and at sunrise at the autumnal equinox (September 22). It is low at the vernal equinox at sunrise and at the autumnal equinox at sunset. About the mean position is reached at the vernal and autumnal equinox at midday and midnight, and also at the summer and winter solstice at six o'clock in the morning and the evening. At the highest and lowest position of the ecliptic it stretches exactly from East to West; at midday at the autumnal equinox, at midnight at the vernal equinox, at six o'clock in the morning at the winter solstice and at six o'clock in the evening at the summer solstice from East-South-East to West-North-West; at midnight at the autumnal equinox, at noon at the vernal equinox, at six o'clock in the morning at the summer solstice and six o'clock in the evening at the winter solstice from East-North-East to West-South-West.

From the above it also follows that at the vernal equinox at sunset the ecliptic presents a *steep angle* to the horizon; at the vernal equinox at sunrise *a slight inclination;* at the autumnal equinox at sunset *a slight inclination;* at the autumnal equinox at sunrise *a steep angle*. At the winter solstice the sun rises and sets about four hours before and after the ecliptic has attained its lowest position in the sky; at sunrise and sunset the position of the ecliptic with respect to the horizon is therefore between mean and slight inclination. At the summer solstice the position is the same at sunrise and sunset as it is at the winter solstice; for the sun rises and sets about four hours after and before the ecliptic has reached its lowest position in the heavens. The reader will do well to have all this well fixed in his mind and not to confuse the apparent orbit of the sun in the sky with the position and shifting of the ecliptic. Thus, for instance, at sunrise on March 21 the angle of inclination of the ecliptic to the horizon is 14½°, at sunrise on September 22, 61½°; but all the same in both cases the sun rises above the horizon at an angle of 38°, so that twilight lasts equally long on both dates. Other important phenomena, such as the visibility of the planet Mercury and of the zodiacal

light, depend, however, upon the position of the ecliptic at sunrise and sunset.[1] With the visibility of Mercury and of the zodiacal light we shall deal later.

It is not difficult to deduce, from the above, at what hours of the day the intermediate stages of the ecliptic occur during the different seasons.

If we are able to find the ecliptic, we shall be able to tell where to look and where not to look for planets. But how do the planets travel in the ecliptic? As we shall presently deal with the planets one by one we shall now only make a few general observations. As a result of the combined movement of the planet and of the Earth, the planet will *sometimes travel from West to East, sometimes from East to West in the ecliptic.* Sometimes it is in "direct" motion, sometimes "retrograde." At times it remains practically stationary for some days among the stars in the sky. If you call to mind the model of the planetary system and set it working in your mind, you will understand why it appears to us like that on Earth.

The Inner Planets

We can divide the planets into two natural groups: those that revolve round the sun *within the Earth's orbit: the inner planets;* and *the outer planets,* whose orbits are *outside* that of the Earth.

The inner planets are Mercury and Venus. We shall first of all have a talk about our beautiful neighbour *Venus.*

Venus

We observed that the planet Venus (diameter 7,800 miles) revolves round the sun at a distance of about 67 million miles in 224½ days. The distance from the Earth

[1] The reader will now gradually be able to understand why the time of the rising (or setting) of the moon on successive days sometimes is no more than ten minutes and at other times no less than an hour and a half later than on the previous day. Thus, the moon, about the time of full moon in the month of September, will rise but a little later every day, owing to the slight inclination of the ecliptic and the comparatively rapid rising of the moon. This phenomenon is even more apparent if the moon is at the same time in the vicinity of the ascending node and hence is a little higher every day with respect to the ecliptic. We call this the "harvest moon."

to the sun is about 93 million miles and it takes a year to circle round it. The best way to imagine how we see Venus from the Earth is first to suppose that the Earth is stationary.

We then at once realize that the distance between Venus and the Earth must vary very considerably. When Venus is at its closest to the Earth (in *inferior conjunction* to the sun) its distance from the Earth is obviously the difference

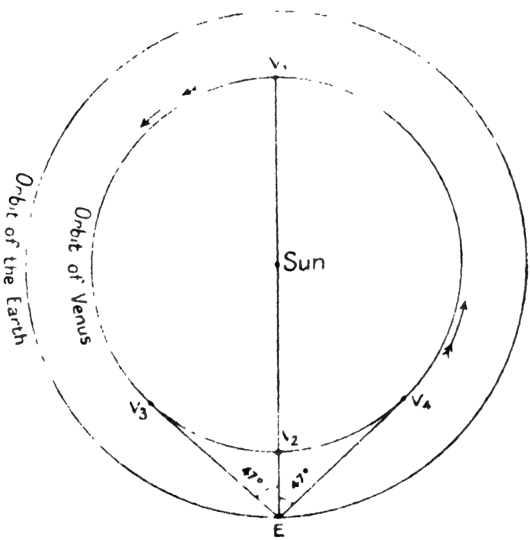


Fig. 27.

V_1 *Venus at superior conjunction.*
V_2 *Venus at inferior conjunction.*
V_3 *Venus at greatest Eastern elongation.*
V_4 *Venus at greatest Western elongation.*
E *Earth.*

between the radii of the orbits of the two bodies, so 93 minus 67 million miles, or 26 million miles; when Venus is as far as possible away from the Earth (in *superior conjunction* to the sun) then its distance from the Earth is the sum of the two radii, that is, 93 plus 67 million, or 160 million miles, which is more than *six* times the smallest distance. Hence the apparent size of the disk of Venus varies very greatly, viz. from 10″ to 66″ (*see* Fig. 27).[1]

[1] The sign ″ means seconds of arc.

We can at once draw several other conclusions from the diagram. When Venus is at inferior conjunction to the sun, *we cannot see it.* For two reasons; firstly because, seen from the Earth, it is in the immediate vicinity of the sun and is completely outshone by the glow of that orb, but even when this is not the case (as during a total eclipse of the sun) it would not be visible to us at inferior conjunction. For, you will remember, Venus, just like the Earth, is a planet and radiates no light of its own. We see Venus because it reflects some of the light that reaches it from the sun. Well, when Venus is at inferior conjunction we might call it "new Venus"; the part lit up by the sun is turned right away from us, it shows us its dark side. Only when, about twice in a hundred years, it passes right over the disk of the sun, can we see it during inferior conjunction projected on the sun as a little black disk with a diameter of just over a minute of arc.

During superior conjunction the visibility of Venus is little better. It is then certainly full, turning its illuminated side straight towards us, but it is as far away from us as it possibly can be, its disk is at its smallest, no more than 10 seconds of arc, and its light is lost in the fierce light of the sun. It is just as rare for Venus to disappear behind the sun as it is for it to pass over the face of the sun.

But it is a different matter when Venus, seen from the Earth, is as far away from the sun as possible. (*See* diagram: greatest Western and Eastern *elongation.*) From the Earth the planet then appears to be (at most) 47° distant from the sun and then rises (on an average) three hours before the sun (when it is called the Morning Star) or else sets three hours after the sun (when called the Evening Star). Under very favourable conditions these three hours may even come to be as much as four and a half hours.

When Venus is in the position of its greatest Eastern elongation, the right half of the Venus disk, seen from the Earth, is illuminated; but the left half is not. Venus appears as a tiny *moon* at *first quarter phase* in the evening sky! In its

greatest Western elongation it is just the other way about, it is then at *last quarter*. So Venus appears *in the same phases* as the moon; but with this difference, that the disk itself changes in size too. We observed that "new" Venus shows the largest disk and "full" Venus the smallest. At "first Venus quarter" the disk has already become a good size: it is apparent from the diagram that this "first quarter" is not half-way between full Venus and new Venus, but much nearer the latter.

These phases of Venus are on the limit of visibility to the naked eye. There are people with exceptionally keen sight who say that they can see Venus as a "half-moon" with the naked eye. The smallest telescope, however, will enable you to see the phases: it is one of the simplest and most satisfying observations that anyone can make. When Galileo (1564–1642) directed his first, very primitive telescope, which had just been discovered, towards Venus he was overjoyed to see that "the mother of Love imitates the phases of the moon!" This proved the correctness of the Copernican theory, at least the incorrectness of that of Ptolemy.[1] (*See* page 58 *ff*.)

Let us now just have a look systematically at the manner in which Venus appears to us. We shall start at superior conjunction. Venus is then full, but too close to the sun for us to be able to see it with the naked eye. Venus then travels farther and farther to the East of the sun and then gradually becomes visible shortly after sunset in the dim light of the evening. Venus sets later and later after sunset until it reaches its greatest Eastern elongation. It then sets about three hours after the sun and is visible as the "Evening Star" as soon as twilight begins. If you know exactly where to find it in the sky, you can see it in the afternoon, before sunset. Indeed, if atmospheric conditions are very good, it is even possible to see it *at midday with the naked eye*. Except for the sun and the moon, Venus is by far the brightest heavenly body. Venus can even throw a shadow—of course it must

[1] According to the Ptolemaic system the illuminated part of Venus could never have grown larger than half the disk.

be very dark for this. I was once able to see this for myself when I was walking along a quite unlighted road in the country and suddenly saw my shadow on a white wall. I was extremely astonished and wondered what light could cause this shadow and found it to be Venus. Of the other planets, only Jupiter can also do this trick when at its brightest. It is seen how bright Venus is at total and even at partial eclipses of the sun. When more than half the sun is eclipsed, Venus can already be seen; when more than three-quarters of the sun is obscured by the moon, the planet cannot fail to draw everybody's attention, unless its position happens to be particularly unfortunate.

We have got to the position of greatest Eastern elongation. Venus moves on towards inferior conjunction and again, from the point of view of the Earth, approaches the sun. It seems to retrace its path. First it moved Eastwards and remained in the sky longer and longer after the sun had disappeared from it, but now it moves Westwards towards the sun and remains a shorter period after sunset every evening. The crescent gets narrower and narrower, too, but this crescent is part of a still growing disk. For some time this growing gains the day and the brightness of Venus increases. Then the reverse happens, the waning crescent begins to emit less light and gradually approaches twilight, from which eventually it can no more detach itself. Then Venus comes to inferior conjunction and is no longer visible to the naked eye. Gradually it reappears again to the West of the sun and manages to escape little by little from the half-light of dawn, so that through a telescope it becomes visible before sunrise in the Eastern sky, in the shape of a small crescent, in the last phase of the last quarter. After some time the position of the greatest Western elongation is reached: then Venus rises three hours, sometimes more, before the sun. It is then the bright "Morning Star." For centuries the Ancients never knew that the Evening Star and the Morning Star were identical. When the point of greatest Western elongation is passed Venus slowly returns to the dawn and

to the sun, waning in size but waxing in phase, to be lost again in the proximity of superior conjunction in the dawn close to the sun.

Thus, continually changing its position and appearance, Venus shows itself to mankind. You would now suppose, knowing that Venus has a period of 224½ days, that inferior conjunction will follow about 112 days after superior conjunction. But this is reckoning without the movement of the Earth. For the Earth travels along its orbit in the same direction as Venus. Venus certainly gets along faster, can therefore "catch up" with the Earth, and does so, but because it does not travel so very much faster, it takes quite a time to do so. Hence the period between superior and inferior conjunction is not 112 days but no less than 292 days. So Venus is Morning Star and Evening Star for a much longer period than it would be if the Earth did not move along round the sun. All this becomes more complicated by the fact that the Earth's orbit is not a circle but an ellipse (the orbit of Venus is practically a circle), and that the orbits of the two planets are not in exactly the same plane. But this does not make any essential difference, so that we need not go into details.

Now we must devote a few words to Venus itself. But the reader will be sadly disappointed if he wishes to know much. We know very little about this planet. We do not even know how long it takes to rotate on its axis, nor what the angle of inclination of that axis is. The planet always appears enveloped in clouds; and other circumstances, too, point to the existence of a thick atmosphere. We know nothing at all about the actual surface of Venus; our vision cannot penetrate to it, not a spot of it has ever been seen by human eye.

Apparently it is now being proved by Lyot's researches at Meudon that Venus is completely surrounded by real clouds built up of fine drops of water. This would mean that the planet is very richly provided with water; it has even been suggested that its whole surface is covered by a coat of

water. But this is largely guess-work. Very roughly speaking, it may be said that the quantity of heat from the sun received by Venus would make it possible for it to bear life as the Earth does. There is certainly no shortage of heat from the sun. But are the other conditions of life, as we know it, fulfilled on Venus? We cannot tell with any measure of certainty.

Mercury

Mercury is—excepting the asteroids—the smallest of the planets, although it is not impossible that Pluto is a little smaller. Its diameter is only 3,190 miles, not very much more than that of the moon; something over a third of that of the Earth. Mercury revolves round the sun in 88 days at a *mean* distance of 36 million miles. We must stress the fact of this being the *mean* distance, as the eccentricity of Mercury is large, as we said before. Its distance to the sun varies greatly.

Almost everything we said relating to Venus also applies to Mercury, but on a much smaller scale. Mercury also, of course, has superior and inferior conjunction to the sun, a greatest Eastern and a greatest Western elongation. Its apparent diameter varies from 5″ at superior conjunction to 13″ at inferior conjunction. But, as seen from the Earth, it remains much closer to the sun and even at its greatest elongations, either as a morning star or as an evening star, it can hardly break away from the half-light of the evening or of the dawn. Never, even under the most favourable conditions, can Mercury, as we see it from the Earth, move farther than 28° away from the sun; it can never set more than two hours after the sun or rise more than two hours before the sun. And usually this time is even less. Besides this, Mercury completes its orbit in 88 days and—although the period between successive Eastern or Western elongation is also in the case of Mercury somewhat longer owing to the Earth's progress in its own orbit—it only remains near its greatest elongation for a few days, and the planet only remains visible as an evening star or a morning star for a few days.

This makes it difficult to observe with the naked eye, especially in a town. But, with plenty of patience, it *is* possible, and one evening I had the good fortune to be able to watch it for quite an hour on end.

In more Southern countries, and particularly in the tropics, observation is easier, not only as a result of the clearer air, but also because the ecliptic presents a steeper angle to the horizon. Accordingly Mercury, although it is still at the same angle to the sun, is higher in the sky and better visible for the two reasons: that the twilight is shorter there and because the planet is higher above the horizon.

The same favourable conditions are approached in our country when the ecliptic is as steep as possible to the horizon. This is the case at the vernal equinox in the evening, at the autumnal equinox in the morning. So, from where we live it is easiest to see Mercury when the greatest Eastern elongation happens to be near March 21, or the greatest Western elongation near September 22. And then there are a few other circumstances that go to make it easier to see it at one time than at another (the inclination of Mercury's orbit and its eccentricity). If then you manage to get a look at Mercury, it will appear in the telescope as a small half-moon, even smaller than Venus and, just as Venus, as the first quarter (evening star) or last quarter (morning star). That Mercury, like Venus, appears in phases will be clear to everybody.

You also stand a good chance of seeing Mercury during a total solar eclipse; and, finally—and this is very interesting —in one of its transits over the face of the sun. These occur much more frequently than those of Venus, even as often as twelve to thirteen times in a hundred years. They always happen either in November or in May. I myself have seen three transits of Mercury: on November 14, 1907, November 7, 1914, and November 10, 1927. The next time will be on November 12, 1940.[1]

[1] On May 10, 1937, there will be a very close approach, but not actually a transit, as is incorrectly stated in some books.

During the transit it is possible to see Mercury very distinctly with the aid of a small telescope. Seen through a small telescope it looks more like a little dot than a disk. And, indeed, its diameter is not much more than $\frac{1}{150}$ of that of the sun. Mercury shows up quite black against the disk of the sun, blacker even than the nucleus of a sun-spot. There can be no mistake about identifying it! This was one of the points that particularly struck me when I observed it: Mercury was a very black, perfectly round, sharply defined dot; any sun-spot appeared grey and irregularly shaped, and having no distinct contours in comparison. One can soon see the planet moving from East to West on the disk of the sun, from left to right. In a few hours' time it passes right over the face of the sun. It is like a little spot of ink passing over the orb of day, a speck of dust, a mere nothing! And yet, one is overjoyed to notice this speck, to have found it! Its passage across the sun is a momentous event to the keen observer, more thrilling than the finest film.

And now we shall have a look at the actual planet. Mercury basks in the light and the heat of the sun, especially at its perihelion, when it is at its closest to the sun. The effect of the sun upon it must be terrific. Its disk is so very small, even under the best circumstances, that we know next to nothing about its surface. In all probability Mercury has no atmosphere at all: as a matter of fact, it resembles our moon in many ways. Its *albedo* (i.e. the fraction of the light from the sun that it reflects) is as small as that of the moon, namely 0·07. This points to similar conditions on the surface. Moreover, Mercury rotates round its axis in the same direction and in the same time as it travels round the sun. Consequently the same side of it always faces the sun, which is also the case of the moon as regards the Earth. The results of this are, of course, perpetual day and more than boiling heat on one side and perpetual night and the bitterest cold on the other. And it is very likely that there is no oxygen and no water there! So on the

whole we even prefer the moon: that at least has alternate day and night!

We may not take leave of Mercury without telling you that it displays an irregularity that greatly puzzled astronomers up to within a few years ago. It is well known that the planets attract one another, thus causing very slight changes (disturbances) in each other's orbits. One of these disturbances is that the perihelion (point in the orbit nearest the sun) is shifted along the orbit. Mercury also has this displacement, but when the influence of the other surrounding planets had been taken into account there was still an unexplained remainder of about 40 seconds of arc *per century*. Of course 40 seconds of arc is not much, but it is enough to give a conscientious astronomer sleepless nights. Numbers of great scientists hunted for an explanation. The most obvious was that there must be some unobserved planet within the orbit of Mercury, perhaps even more than one, that caused this disturbance. Consequently the heavens were scanned for intra-mercurial planets. Some seekers gazed at the sun hoping to catch the unknown planet passing across it; others hoped to discover it during a total eclipse of the sun. But it was all in vain, the 40 seconds of arc remained a mystery; astronomers were unable to account for it.

Until Einstein came with his relativity theory. The principle on which this theory was based had nothing at all to do with Mercury; Einstein might have formulated it without ever having heard of Mercury. The theory was founded upon the established fact that the rate of the Earth round the sun has no influence upon the *velocity* of light with respect to the Earth. So the theory had been drawn up to explain quite different phenomena. But then, when the formulas that Einstein founded upon his theory were applied to Mercury's orbit, the 40 seconds' difference vanished into thin air: Mercury was in the exact position it should be according to the new theory.

The reader will think, surely this means that Einstein

disproved Newton's universal law. But, as we said already, *this is not the case.* Einstein regards the physical phenomena, including the law of universal gravitation, from quite a different angle. However much Einstein's theory may differ in aspect, his results are the same in practice as Newton's. How else could it be possible that Newton's laws have proved faithful guides in all matters pertaining to the prediction of astronomical events through several centuries? It is only in extremely exceptional cases that Einstein's theory leads to results that vary in actual practice from Newton's law. This happens at velocities that approach that of light and also under the influence of a very powerful gravitational attraction. This latter is the case with Mercury, which is so close to the enormous globe of the sun. Here Einstein differs by 40 seconds of arc in a century from Newton. But for the other planets the difference has almost been eliminated again.

This does not detract from the fact that the solution of the problem of Mercury's 40 seconds of arc is one of the finest triumphs of Einstein's theory.

THE OUTER PLANETS

Mars

We have paid a call upon our neighbour Venus; on the other side lives our neighbour Mars. Mars can be distinguished in the sky by its reddish hue; it is the only planet that has this reddish hue; that is why it was given the name of the fiery god of war. We observed that Mars completes its journey about the sun in 687 days, almost two years, at a mean distance of 141 million miles. We have got so far that we should have been able accurately to calculate this period of revolution if only we knew its distance (ratio to distance from Earth to sun, Kepler's third law). Mars is a small planet, its diameter is only 4,200 miles. So its volume is $\frac{1}{7}$ to $\frac{1}{8}$ of that of the Earth, three times that of Mercury, $7\frac{1}{2}$ times that of our moon. Its mass is something more than $\frac{1}{10}$ of that of the Earth; hence the substances

of which Mars is built up are on an average lighter than those of which the Earth is constructed.

How does the orbit of Mars stand with regard to the Earth? This is quite simple to find: its orbit lies outside that of the Earth. The Earth takes a year to cycle round the sun, Mars nearly two years. So the Earth completes a shorter orbit in a shorter period. We shall watch these orbits, starting from a moment when, seen from the sun, both bodies are observed in exactly the same direction. The Earth is then as close as possible to Mars, the distance between them being equal to the radius of the orbit of Mars minus that of the Earth. Mars is then in opposition to the sun. It must be kept in mind that the Earth is not always at the same distance from the sun; nor is Mars either in fact there the difference is greater still. So one opposition can bring Mars a great deal closer to us than another. If Mars is very favourably placed its apparent diameter increases to as much as over 30 seconds of arc. The distance from the Earth to Mars is then only 31 million miles. During an opposition Mars shines as a particularly fine star in the sky at night.

The Earth travels more rapidly round the sun than Mars does. In Fig. 28 you can see how, seen from the Earth, Mars does not always appear to move in the same direction across the vault of heaven: sometimes the planet is "in direct motion," sometimes (i.e. near opposition) it "retrogrades." First the Earth sees the planet in M_1 (dotted in Fig. 28) against the background of sky, then in M_2 (dotted). Between these points the planet is "in direct motion"; then it "retrogrades" from M_2 (dotted) to M_3 (dotted) and then moves forward again in direct motion between M_3 (dotted) and M_4 (dotted). The Earth and Mars run a race round the sun, the Earth constantly gaining; that the Earth finally succeeds in reaching exactly the other side of the sun to Mars, thus seeing Mars in conjunction with the sun, is not due to Mars, but to the movement of the Earth. If Mars were to be stationary with respect to the sun, the Earth would

be able to see Mars in the position of conjunction in six months' time from opposition; Mars retards this process by revolving too, so that the Earth must run much farther to get Mars into the position of conjunction. It requires 390 days to do this; therefore the time elapsing between two oppositions is 780 days, or more than two years. The

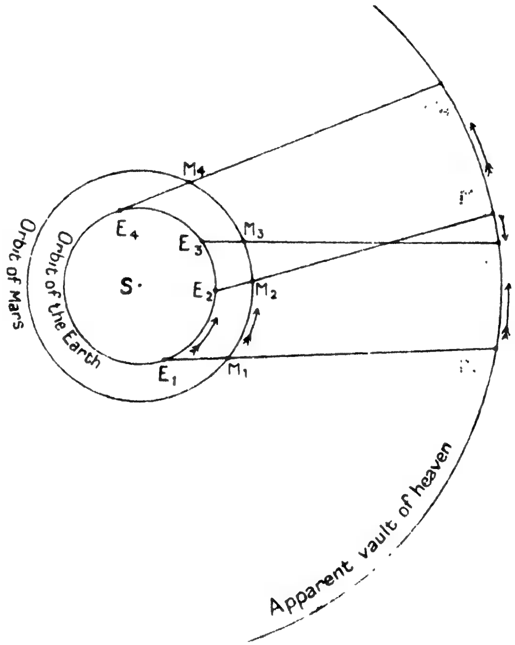


Fig. 28.
The apparent motion of Mars in the vault of heaven is direct from M_1 to M_2, retrograde from M_2 to M_3, and direct from M_3 to M_4.

slower the rate of an outer planet is the less influence it will have upon the interval elapsing between two oppositions (upon the *synodic* period of revolution, that is, period of revolution with respect to the Earth) and the greater will be the influence of the period of the revolution of the Earth itself. The farther away a planet is, the slower is its rate of revolution round the sun. That is why the influence of the period of the Earth upon the synodic period of a planet grows

greater in proportion as that planet is farther removed from us. Or, in other words, the synodic period of the outer planets, the interval between two oppositions, differs the less from a year in proportion as the planet is farther away from us. In the case of Mars it is as much as 780 days, of Jupiter no more than 399 days, of Saturn 378 days, of Neptune no more than 368 days. So, with the exception of Mars, the outer planets move slowly with respect to the stars. Neptune even stays more than 10 years in one same sign of the zodiac.

But let us return to Mars. We should like to see what exactly happens during a synodic period of Mars, *i.e.* in the period of 780 days. As we have found out that the motion of the Earth plays the most important part in this process, we can greatly simplify matters by supposing Mars to be stationary. The principal phenomena will then occur just the same, though in a shorter time than is actually the case. From opposition the Earth travels on, counter-clockwise as we know, round the sun. After some time has passed Mars appears to us in a phase, we begin to see it slightly from one side with respect to the sun. But the phases are not so pronounced as those of the moon; soon we again see a larger part of the illuminated disk. The surface that we see of the disk of Mars is never less than about $\frac{4}{6}$. Mars then appears something like the moon three days before full moon. The diameter of Mars, as the Earth travels away from opposition, becomes smaller and smaller. Besides this the rising and setting of the planet take place earlier and earlier. Suppose opposition happened to occur during the equinox, then Mars would rise at about 6 o'clock in the evening, and would set at about 6 o'clock in the morning. When its position has altered so much that the planet is half-way between opposition and conjunction it rises as early as before midday and sets before midnight. So it has "caught up" more than six hours with the sun; it has approached the sun in a Westerly direction. But (in reality a quarter of the 780 days have passed, so we are more than six months farther) in the meantime the

stars have gained more than twelve hours upon the sun. So the planet approaches the sun in a Westerly direction while at the same time it moves to the East with respect to the stars, not counting a temporary "retrogression" in the vicinity of opposition. This is, broadly, how the outer planets travel, each with its own particular variations. As regards their phases, these can also be observed in the case of Jupiter, but the reader will readily understand (just draw the orbits!) that they are even less significant than of Mars. In the case of the other planets they practically cease to play any part at all.

The Earth continues its revolution and thus the position of conjunction of Mars with the sun is reached. The Earth is now as far as possible away from Mars: it is the sum of the radii of the two orbits, or, almost 250 million miles, seven times the distance they are away from each other in opposition. Moreover, Mars is no longer visible to the naked eye, for it rises and sets with the sun. During the period immediately preceding conjunction it sets sooner and sooner after the sun, thus disappearing in the twilight of the evening. After conjunction it gradually begins to rise before the sun, detaching itself farther and farther from the dawn.

Every day at sunrise it is higher and higher in the sky, until it rises at midnight and sets at noon. Then the phase becomes distinctly visible again, this time in the phase of the moon three days after full moon. And, finally, opposition is reached again: Mars sets at sunrise, rises at sunset and is high in the sky at midnight.

So all outer planets detach themselves from the dawn after their conjunction, becoming gradually more and more visible, first during the latter part of the night, then during the whole night, then during the first half of the night, finally to disappear in the twilight when the next conjunction is approaching. The farther they are removed from the sun, the more quickly do they complete this process and the more they gain upon solar time, thereby losing less with respect to sidereal time.

A word as regards the progress in direct motion and the retrograde motion of the outer planets. As the retrograde motion is not real but only an apparent motion in perspective, it will appear less marked as the planet is farther away from us. And seeing that the planes of the orbits of the planets are oblique with respect to that of the Earth this "direct motion" and "retrograde" motion will not be absolute backward and forward movements along the same path, but either a loop or an S-shaped motion.

The various particulars about the surface of Mars are known fairly exactly. Hence we can also determine its rotation upon its axis; this happens in 24 hours 37 minutes and 23 seconds in the same direction as that of the Earth. So that is the duration of the sidereal day on Mars, the solar day is a little longer: 24 hours 39 minutes and 35 seconds. So the difference is only a little over two minutes, about half of what it is on Earth. This is just what we should expect, the year of Mars being almost twice as long as ours.

So we see that the difference between our day and that of Mars is only a good half-hour. In ordinary everyday life this would make little difference. So in this respect the two planets resemble each other strongly. As indeed they do in other ways too. The angle of inclination of Mars's axis (with respect to *the perpendicular to the orbit*) is known. The reader knows how extremely important this angle of inclination is as the cause of the different seasons and for the climates on different parts of the globe. And now it appears that the angle of inclination of Mars is about 24°, as compared with 23° 27′ on Earth. Another great similarity.

So Mars has tropics and tropical zones, a North and a South Pole, which in many ways resemble those of the Earth. On the two hemispheres of Mars spring, summer, autumn and winter must alternate just as they do on Earth, with exactly the same contrast between the Northern and Southern hemispheres. There are two great differences:

the year on Mars is almost twice as long as on Earth and its orbit is more eccentric than that of the Earth, which means that the seasons are of very unequal length. Here is a list with the lengths of the seasons given in days (it refers to the Northern hemispheres of the two planets):

	Duration of the Seasons				
	On Earth			*On Mars*	
Spring	93	Earth days	..	191	Martian days
Summer	93	,, ,,	..	181	,, ,,
Autumn	90	,, ,,	..	149	,, ,,
Winter	89	,, ,,	..	147	,, ,,
	365	,, ,,	..	668	,, ,,

And should you perhaps think that it needs some imagination to compose such a table, we may assure you that it is easier to observe the changes on Mars than on our own planet. On the Earth we must either go to the place in question to observe the changes or else resort to our model room. But to observe Mars all we need is a good telescope! We can observe how long the days are at various seasons of the year and in different places on the surface of Mars—we see an ice-cap formed during the Northern or Southern winter at either of the Poles, we see the midnight sun shining and the Polar ice melt away in spring and summer! But we prefer to leave the description to the visitor who actually went there and saw it all with his own eyes. (*See* Chapter VII.)

Mars has *two moons*—we are now for the first time making the acquaintance of a very remarkable phenomenon. We are so used to talking about the moon. We should really speak of our moon, as we should, to be correct, also speak of our sun, because every star is a sun, but situated at a distance millions of times farther away. A moon, or satellite, stands in relation to a planet as the planet does to the sun. If the planets are children of the sun, the moons or satellites are children of the planets, so grandchildren of the sun. The Earth has one child: one moon; Mercury and Venus have none; the other planets have fairly large, some of

them very large, families. Our knowledge of the families of Jupiter and of Saturn has been enlarged within the last twenty years. And so it is within the range of the possible, though not probable for reasons we shall mention later, that the farthest outer planets have more than have yet been discovered (of Neptune we only know one, of Pluto not even one).

Mars has two moons. Up to 1877 it was thought that Mars had no satellites. But in that year the American astronomer Hall discovered the two satellites, during a favourable opposition. That they had never been seen before must be attributed to the fact that they are very small and very close to Mars. The following facts are known: the nearest, called Phobos, revolves round Mars at a distance of no more than 5,800 miles[1] in a period of 7 hours, 39 minutes. That is to say, that it revolves more rapidly than the apparent motion of the vault of heaven on Mars (a result of the axial rotation of Mars in 24½ hours) and so—a rare phenomenon in the solar system—it rises in the *West* and sets in the *East*. The outer moon, Deimos, revolves round Mars at a distance of 14,600 miles in 30 hours and 18 minutes, and hence rises in the East and sets in the West, behaving in the conventional way!

The orbits of both moons are about circular. These bodies are extremely small. It is hard to estimate their exact diameters. The inner one appears to be the larger and to have a diameter of about 9 miles.[2] The diameter of the outer moon is probably no more than about 7 miles. These are "worlds" on which, travelling at the same rate as on Earth, one can complete a trip "round the world" on foot in seven to nine hours!

Jupiter

The giant among the planets! Its diameter is about 87,000 miles, or more than 10 times, and its volume about

[1] These 5,800 miles are calculated from the centre of the planet. This is always done in indicating the radius of the orbits of a satellite. The distance from the surface is under 4,000 miles.

[2] Recent estimates make it a little more.

1,280 times that of the Earth. It has the same density as the sun, and its temperature was formerly held to be very high, but later research had made this doubtful. At a distance of 483 million miles from the sun, Jupiter completes its orbit round the sun in nearly 12 years.

At opposition the planet can approach the Earth to within 390 million miles; at conjunction it is more than 570 million miles away from us. At opposition the diameter of the disk is 38″. It then appears as a brilliant "star" in the firmament. There are only three heavenly bodies more brilliant than Jupiter: the sun, the moon and sometimes Venus. Jupiter, like Venus, can cast a shadow. We observed already that there are 399 days, over 13 months, between two oppositions.

Jupiter rotates round its axis very rapidly, namely in about 9 hours and 55 minutes. Owing to the velocity of its rotation the planet is much flattened, as much as $\frac{1}{17}$, while we know that this flattening is only $\frac{1}{300}$ in the case of the Earth. Upon the surface of Jupiter certain belts, or rather, markings running as belts, are visible. In all probability we do not ever see the actual surface at all; what we see are probably clouds drifting high in the atmosphere of Jupiter.

Among astronomers Jupiter is famous for its moons. At present nine are known,[1] four of which have become famous in the history of astronomy. These four are large; they are on the boundary-line of visibility with the naked eye; some people with very keen sight can see one or more of them without looking through a telescope. Through a pair of good field-glasses they may be seen very clearly and make a fine sight, specially during opposition: the planet itself is then seen as a bright, clearly defined disk with four fine astral points near it, the satellites.

As soon as the telescope had been discovered and Galileo directed his instrument towards Jupiter, he discovered the

[1] Two of the smallest of the moons travel from East to West, which is an extremely exceptional motion in the solar system.

satellites. At first sight it was possible for him to regard them as fixed stars happening to be in the vicinity of Jupiter, but soon he saw what they really were: they followed the planet, belonged to it and within a short time revolved round it! Galileo saw the solar system in miniature before him and now we can all see it if we wish to. The first time we observe it, it is truly a revelation, even though our satisfaction cannot be as great as that of Galileo or of Marius, who made the same discovery as Galileo at about the same time! Here is a list of Jupiter's children, omitting those found much later, which are very faint indeed and only visible through a very powerful telescope.

	Distance from the centre of Jupiter in miles	*Period d. h. m.*	*Diameter in miles*
I. Io	262,000	1 18 28	2,470
II. Europa	417,000	3 13 14	2,060
III. Ganymede	664,000	7 3 43	3,580
IV. Callisto	1,169,000	16 16 32	3,360

Quite a respectable family! Ganymede and Callisto are even larger than Mercury. Io is somewhat larger, Europa is a little smaller, than our moon (whose diameter is 2,160 miles), and the other two are considerably larger. In proportion to Jupiter, they are, however, much smaller than the moon in proportion to the Earth. As a matter of fact our moon, as regards its size in relation to its planet, is unique in the solar system, being far larger than any other.

Now if we read in the paper or in some astronomical journal that Jupiter is well visible at night, we look for it in the ecliptic. If we are familiar with the constellations we at once find the foreign temporary guest. If we do not know the constellations sufficiently for this purpose, it will all the same be quite a simple thing to find Jupiter. We know where the ecliptic is (*see* page 173). It is in that belt that we must look, and then it is almost impossible to miss it. We see a very radiant heavenly body, more luminous than any "fixed" star. It does not twinkle; planets do not sparkle

and twinkle, their light is steady, only the fixed stars twinkle and glitter. This is because even the largest fixed stars are so far away from us that they only show as infinitesimal specks to our eye (and for that matter through the largest telescopes). Any irregularity in the atmosphere intercepts the course of that immeasurably thin ray of light to our eye: that is why the star cannot send its rays to us steadily. But a planet, even though it is so much smaller than a fixed star, is millions of times closer to us, so that it is not a mere speck but a very small disk in the sky. A *number* of rays of light simultaneously reach our eye and these are not all intercepted at the same time or in the same degree by irregularities of the atmosphere. And so we see a kind of average light from a planet, which appears quite steady to our eye, because the twinkling of one ray is eliminated by another.[1]

So that star, that bright star shining so steadily in the ecliptic, must be a planet. It cannot be Venus (we know that Venus never sets later than about four hours after the sun, and so, when it is dark, is always low in the sky). It cannot possibly be Mercury. Mars has a reddish colour. That only leaves Jupiter and Saturn; of course it is superfluous to say that this bright body cannot be either Uranus or Neptune. It is not difficult to make up our minds between Jupiter and Saturn: Saturn never becomes as bright as Jupiter.

But, if we still hesitate between Jupiter and Saturn, we need only take a look through our telescope to find out which it is. This removes all doubt. We can clearly see the planet as a disk, and the four satellites as tiny stars near it. It must be Jupiter!

But it is also quite possible that, looking at Jupiter through a telescope on a fine night, you see not four stars near it but only three, or two. It may even happen, although this is rare, that only one can be seen, or, rarer still, none

[1] Under unfavourable conditions, when the atmosphere is very agitated, or when the planet is very low in the sky, a planet sometimes also twinkles, the more so as its disk is smaller. In particular Mercury sometimes twinkles in a way unbecoming to a planet.

at all. How can this be explained? The reader will probably already have realized how this can be. As we saw above, the four moons revolve round Jupiter with great velocity and they travel approximately in the orbital plane of Jupiter, which almost coincides with the ecliptic. So to our sight they must repeatedly disappear behind the planet (occultation) or pass exactly across its face (transit), or else, without being covered up by the planet, they are eclipsed by Jupiter as they pass through its shadow. As they revolve practically in the orbital plane of Jupiter they are even eclipsed at every revolution, at every full moon. Only number IV sometimes makes an exception. When Jupiter is exactly at opposition occultation and eclipse coincide; the sun, the Earth, Jupiter and the satellite are all in one line of sight. But at other points of Jupiter's orbit the eclipse of the satellite can begin (the sun, Jupiter and the satellite are then in one line) while that moon, for our line of sight from one side, is not yet covered up by Jupiter. Or else the eclipse can continue while its moon is no longer covered for our line of sight by Jupiter. So then we cannot see it either, for the eclipse is a real phenomenon, the satellite loses its light (because it is in Jupiter's shadow and hence reflects no sunlight) and is not visible from any point in the Universe. We explained all this when it concerned *our* moon. When a moon passes in front of Jupiter we do not see it either; only through a powerful telescope it is occasionally possible to see the disk of the satellite on a very light or very dark spot of Jupiter.

So Jupiter's satellites may be invisible to us for the reason that they either pass in front of Jupiter, or are hidden from our view behind it, or are eclipsed in its shadow. So it may, very occasionally, happen that all four satellites are in one of these three conditions. Besides this we can often —but only through a fairly large telescope—see a fourth eventuality, namely a shadow transit; we then see the shadow of one of the moons passing across the face of Jupiter; we see a total solar eclipse on Jupiter.

As a rule, however, all four moons will be visible. It is very interesting to watch how their positions change every night. Indeed, even at the end of a few hours the inner moon at least may be seen to have altered its position. It almost seems as though, to illustrate the solar system, Nature has been so kind as to construct a small planetarium for our convenience.

Determination of the Velocity of Light

The eclipses of the satellites of Jupiter have become famous in astronomy and in physics. For it was by their means that it became possible to determine the velocity with which light travels. For light also requires time to reach us, though it travels with amazing speed. That sound requires time to reach us is a thing we have observed from many events in everyday life: the peal of thunder accompanying the flash of lightning is only heard some time after we have seen the flash, the difference in time between flash and sound being proportionate to the distance of the discharge from us. We see the smoke of a rifle or a big gun before we hear the sound of the shot. The echo takes time to reach us. Sound travels at the rate of over 300 yards a second; light travels, just as wireless waves do, a million times faster, at a rate of 186,000 miles per second. Hence the light of the moon reaches us in a little over a second, the light of the sun needs about 8 minutes to get to the Earth. Nowadays the speed of light is exactly known, but in olden times that was not the case. Many people, if not all, would have shaken their heads incredulously if anyone had assured them that light did not travel at unlimited speed.

During the eclipses of Jupiter's satellites, matters are as follows: the moment that an eclipse begins can be accurately calculated (that is, the moment when the satellite disappears in Jupiter's shadow), because the periods of that moon are known with great precision. But now it transpires that this moment when we see the beginning of the eclipse does not tally with our calculations. Near opposition, the eclipse

comes more than 35 minutes late, near conjunction as much as over 50 minutes. That is too bad, even in everyday life. In astronomy, where it is the custom to think precisely in seconds or fractions of seconds, it is a monstrosity, unless a sound explanation can be found for it. Well, there *is* an explanation; it is even obvious. When Jupiter's satellite enters its shadow, at the exact moment of complete envelopment it sends its last ray of reflected sunlight to the Earth. But this ray requires a certain time to reach us; when the distance from Jupiter to the Earth is as small as possible (opposition) the ray travels this distance in 35 minutes; but if the distance is as long as possible (conjunction) it takes as much as 51 minutes to reach us. The difference between the shortest and longest distance, as the reader knows or will at once understand, is exactly twice the distance from the Earth to the sun. From this it follows that light travels the distance from the Earth to the sun, or from the sun to the Earth, in 8 minutes. As this distance was already fairly well known at the end of the seventeenth century when this discovery was made, the velocity of light could be calculated.

And yet the phenomenon was discovered somewhat differently, and could not but be discovered differently. We shall soon realize that, if we imagine how the eclipses of Jupiter's moons would be seen if the distance from Jupiter to the Earth were constant, if, for instance, it were always equal to what is now the mean distance. The eclipses would then invariably come 43 minutes late. Quite right! But then it will also be clear that *this would never be noticed!* For we should always see a Jupiter satellite at a point of its orbit where in reality it had been 43 minutes before. The whole revolution would be observed by us exactly true to fact, but retarded 43 minutes. And nothing would enable us to perceive this discrepancy if we did not know of the velocity of light.

But matters change owing to the fact that the distance from the Earth to Jupiter is not always the same. In 1675,

the Danish astronomer Roemer wished to establish the time elapsing between two successive eclipses of each of Jupiter's satellites. To this end he collected data of a great number of observations of these eclipses and found that these times rather varied. In order to be able to predict future eclipses with great precision, he took the average of these times with respect to each of the moons and corrected observations that had been made accordingly. On this principle he was able to draw up new tables for future eclipses. And now it transpired that the eclipses came 8 minutes early during opposition, and 8 minutes late during conjunction. Roemer then, with the insight of genius, did not hesitate to attribute this disparity to the non-infinite velocity of light!

In these days, when it is possible to measure the speed of light here on Earth in our laboratories, we can work the other way about and employ the known velocity of light to determine the distances in the solar system, the distance from the Earth to the sun in particular, by the aid of the data provided by Jupiter's satellites when they arrive too late.

Careful observation of the satellites of Jupiter has shown that they constantly display the same side to the planet. So in this respect they behave in the same way as *our* moon: during one revolution round Jupiter they also rotate once round their own axes. The same cause responsible for it in the case of our moon must have been at work here too. (*See* page 108.)

Saturn

Saturn is the largest but one of the planets. Its greatest diameter is 74,900 miles and it takes 29½ years to travel round the sun, at a distance of 886 million miles. To the Ancients, and indeed until the discovery of Uranus by William Herschel (1781), it was known as the farthermost planet of the solar system. Saturn is very much flattened at the Poles, more so than any other planet, this flattening

being no less than $\frac{1}{10}$. Its rotation is very rapid, it is completed once in 10 hours and 15 minutes. Owing to the flattening its volume is less than its equatorial diameter would lead one to suppose: the volume is only 719 times that of the Earth.

Saturn is a magnificent object, even through only a medium-sized telescope, fully deserving the name of "the wonder of the solar system." Not only because it has no less than eight satellites around it (and of late one more very tiny one has been discovered) but its famous ring is an extremely interesting sight in a telescope (except in the particular cases mentioned below when it cannot be seen). The planet itself can be observed clearly as a small disk. Its diameter varies from 15″ to 20″, from conjunction to opposition.

The ring was for the first time observed as such by the Dutch scientist Huygens, in 1655. Galileo had previously perceived, when he directed his small telescope upon Saturn, that there was something the matter with it. He recorded that he saw it as a triple body. You can undergo exactly the same sensation at the present day, if you look at it through a pair of opera glasses. You will then see—I know this from experience—that there is something peculiar about the disk: on either side there is a kind of protuberance; it really has a threefold appearance. But a small astronomical telescope shows the ring.

It is possible, however, that even through a powerful telescope, the reader will look in vain for the ring. The ring encircles the equator of the planet. Its position is constant with regard to space. The plane of the ring presents an angle of 28° to the ecliptic. What consequence has this during a revolution of Saturn about the sun in about thirty years? If you cut a cardboard ring in the shape of Saturn's ring you can make a test yourself. Ask a friend to hold up the ring and walk round you in a circle. He must hold the ring on a level with your eyes, at an angle of about 30° to the floor, and in such a way—this is what matters—that

upon the ring revolving round you, the angle of its axis in space remains unchanged. In other words, the ring must remain constantly parallel to itself. If the test is carried out properly, during part of the revolution you will be looking on to the upper side of the ring, during another part up against the bottom of it, and at two points of its journey, two small parts of the revolution, you will be looking exactly at the edge of the ring.

The latter stage occurs once in 15 years, for Saturn's period of revolution is 30 years; the rings are edgeways on when Saturn is in the constellations of Leo and Aquarius. The ring is then (comparatively) so thin (not more than at most 45 miles) that it is no longer visible excepting through very powerful telescopes. You will understand that exactly 7½ years before and after this time, when Saturn is in Taurus or Scorpio, the ring is at its widest and as well visible as it can be. At present (1936) we are approaching a very unfavourable position for observation.

If the ring is observed through a strong telescope when it is well visible, it will be seen that there is not one ring, but at least three concentric rings. The outer ring is not the brightest of the three; it is separated by a distinctly defined dark division from the second ring, which is the brightest; then comes the third, which is much fainter. Behind the planet a part of its shadow can be seen on the ring, so that the ring itself cannot be luminous, but just like the planets and their satellites it is only seen by reflected sunlight.

The question as to what might be the nature and composition of this rare phenomenon occupied the minds of astronomers for a long time. Nowadays it has been established that it consists of an immense number of minute moons or satellites. This has been proved in a number of ways varying widely. Observation of the brightness of the ring has shown that its changes in brightness can only be understood and explained if allowance is made for shadows thrown by separate particles one upon the other. The following proofs are particularly convincing and quite simple.

Firstly, if Saturn's ring were actually one solid ring, the outer edge would have to revolve with a higher velocity than the inner edge as it turned round the planet (we have not yet said that it does revolve round the planet, but our readers know that this is a matter of course, as otherwise it would fall on to Saturn). But if, on the contrary, it consists of a very great number of separate satellites, then, in obedience to Kepler's third law, it is the *outer* ones that must revolve more slowly. And this is exactly what has been ascertained on the strength of accurate observation; the inner parts of the ring prove to revolve at a rate of 12½ miles per second, the outer at 10 miles per second.

And secondly, it has several times happened that stars that Saturn passed by remained visible through the ring, even through the brightest parts of the second ring, though the luminosity of these stars was reduced by about ¾. So the ring is transparent, for the reason that it consists of an incalculable number of separate fragments, minute satellites. And yet it is dense enough to cast a distinctly visible shadow upon the planet.

The dimensions of the three rings are as follows:

	External diameter of the ring, in miles	*Width of the ring in miles*
Outermost ring	170,000	10,000
Middle ring	146,000	16,000
Innermost ring	113,000	11,000

We may not take leave of Saturn's rings without recording that nowadays it is considered almost as an established fact that they are the remains of what was once a moon belonging to Saturn, which exploded. For it can be mathematically proved that a moon approaching too close to a planet, nearer than a certain mathematically-determined limit, is doomed to destruction by the forces then at work. This is called *Roche's* limit. If a satellite approaches a planet closer than 2·45 times the radius of the latter, the satellite is doomed. And see, Saturn's outermost

ring is no more than 2·30 times the radius of Saturn distant from the planet, so that it is well within the limit. The innermost part of the inner ring is only about 8,000 miles from the surface of the planet. The total mass of all the satellites of which the rings are built up, cannot be great; otherwise the ring would cause a much greater disturbance in the orbits of the moons of Saturn than is now the case. So one must imagine the fragments as mere pebbles, or perhaps even as only grains of sand. Yet the brightness of Saturn is greatly enhanced by the lustrous ring; if the position of the ring is favourable, the light we receive from the planet is about three times as strong as when it is unfavourable.

No less than nine moons of Saturn are known at present.[1] Titan, the largest, was discovered as early as 1655, by Huygens. Its diameter is about 3,000 miles, and hence it is larger than our moon. Its distance from the centre of Saturn is about 759,000 miles and it takes 15 days, 22 hours, 41 minutes and 23 seconds to revolve round the planet. Titan can be observed through quite a small telescope.

Below is a complete list of the satellites:

Name	*Discovered in*	*Discovered by*	*Distance in terms of Saturn's radius*	*Period* d.	h.
Mimas	1789	W. Herschel	3·1	0	23
Enceladus	1789	W. Herschel	3·9	1	9
Tethys	1684	Cassini	4·9	1	21
Dione	1684	Cassini	6·2	2	18
Rhea	1672	Cassini	8·7	4	12
Titan	1655	Huygens	20·2	15	23
[Themis[1]	1904	W. H. Pickering	24·2	20	20]
Hyperion	1848	Bond	24·5	21	7
Japetus	1671	Cassini	58·9	79	8
Phoebe[2]	1898	W. H. Pickering	214·4	550	11

[1] The discovery of a tenth moon, Themis, by Pickering in 1904 has not been confirmed.

[2] The motion of Phoebe is from East to West, unlike almost any other in the solar system. Also *see* the note on p. 206 about Jupiter's two satellites, and page 217.

Uranus

Compared with the Earth Uranus is also a large planet. Its diameter is about 31,000 miles. Hence Uranus has about 59 times the volume of the Earth. It revolves round the sun at a distance of 1,800 million miles in a period of 84 years. Its sphere is flattened by about $\frac{1}{16}$; it has now been established that it rotates round its axis in about $10\frac{3}{4}$ hours in the wrong direction, that is, from East to West. Every motion that we have observed so far in the solar system is from West to East, with the exception of the motions of Phoebe, one of Saturn's satellites, and of two of the recently discovered satellites of Jupiter. But the exception we have here is certainly of more importance.

Uranus appears in the sky as a disk with a diameter of about 4″. Under favourable conditions it can be just visible to the naked eye as a very faint star.

The Ancients did not know Uranus. It was discovered by William Herschel in 1781. Herschel (1738–1822) was originally a German musician, who emigrated to England and applied himself to the study of mathematics and astronomy. He constructed magnificent telescopes, gradually making larger and more powerful ones. Finally, he made one almost 40 feet long, with an opening of 4 feet. Herschel was one of the greatest astronomers of all time.

On March 13, 1781, as Herschel was watching part of Gemini through one of his reflectors, he noticed a heavenly body there whose shape was distinctly that of a disk. We have already explained elsewhere that the fixed stars, owing to their immeasurable distances, are only visible as infinitesimal specks even through the best telescopes (if sharply focused!). So when this body proved to possess a measurable diameter, it could not possibly be a fixed star and Herschel thought that it must be a comet, as he did not dare to dream that there could be any planets besides the ones that had been known for thousands of years. But after some months, when the orbit had been computed, this thoroughly unexpected

fact had to be accepted and it was found that the newly-discovered body was a planet. After some argument it was dubbed *Uranus.*

When the orbit of Uranus was completely calculated it appeared that the object had been observed previously, several times even. It had always been looked upon as an "ordinary" star, however. And indeed, even through a small telescope Uranus is visible as a star.

Herschel also succeeded in discovering two satellites of the planet, to which he gave the names of Oberon and Titania. In 1851 Lassell discovered two more (Ariel and Umbriel). They can only be observed through powerful telescopes.

The orbital plane of these satellites is almost at right angles to the ecliptic: the angle is 82°. Perhaps it would be more correct to say 98°, for the direction in which all four satellites revolve is the opposite to that which is "normal" in the solar system.

In former times a great deal of weight was attached to this point. Saturn's ninth satellite (Phoebe) and the two retrograde satellites of Jupiter had not yet been discovered, nor was the "wrong" rotation of Uranus itself known. So, then, this uncommon motion of the satellites of Uranus and that of Neptune's moon were the only known exceptions to the prevailing direction of motion in the solar system. This universal sameness in the direction in which heavenly bodies revolved seemed to be one of the most convincing proofs in favour of the *nebular hypothesis*, a theory originated by Kant and developed by Laplace, by which our solar system was supposed to have been formed from the masses of a rotating gaseous nebula of extremely high temperature. The wrong direction of the motion of the satellites of Uranus was a serious objection to this theory. In our times the nebular hypothesis is considered as antiquated and has been practically discarded. Hence the exception, to which some more have been added, has lost a good deal of its former importance.

These are the four satellites:

	Distance from Uranus in miles	Period d.	h.	m.
Ariel	119,000	2	12	29
Umbriel	166,000	4	3	28
Titania	272,000	8	16	56
Oberon	364,000	13	11	7

Neptune

Until very recently Neptune was considered as the last planet of our solar system. It travels round the sun at a distance of about 2,800 million miles in a period of upwards of 164 years. Compared with the Earth, Neptune is also a large planet; its diameter is about 33,000 miles. It is about seventy times as large as the Earth. Probably it rotates round its axis in 15 hours, 45 minutes in the wrong direction, East to West. It appears in our sky as a disk with a diameter of 3 seconds of arc. It is never visible to the naked eye, but with a medium-sized telescope it is easy to find.

So far as we know, Neptune has only one satellite. This was for the first time observed, shortly after the discovery of Neptune itself, on October 10, 1846, by Lassell. It revolves round Neptune in 5 days, 21 hours, at a distance of 248,000 miles from the planet, and it also moves in the wrong direction! From East to West! This was another objection to the nebular hypothesis. Neptune's satellite is large; it appears to have a diameter of 3,100 miles.

The most famous chapter in the history of Neptune is that which records its discovery almost simultaneously by the Frenchman, Leverrier, and the Englishman, Adams. The discovery of Neptune may even be said to be one of the finest pages in the whole science of astronomy and of science in general. For how was it found? Not, like Uranus, more or less by chance. *Neptune was discovered on paper, in the study*, by the application of mathematical formulæ.

We mentioned before that the planets attract one another, causing perturbations in each other's orbits. In particular the orbit of Uranus displayed perturbations. Close study

of Uranus's orbit and careful calculation of the perturbations that Saturn and Jupiter could not but cause in Uranus's orbit (the disturbing effects of other planets were negligible) showed that there must be some other factor to account for Uranus's position in the sky. There must be some other influence at work; obviously there was an unknown planet in a position likewise unknown that was the culprit ! Leverrier set to work and, it is said, spent almost two years working out all kinds of mathematical formulæ. On August 31, 1846, he had finished his calculations and submitted the results of his study to the French Academy. According to him the unknown planet must be in a position 5° to the East of the star δ of Capricorn.

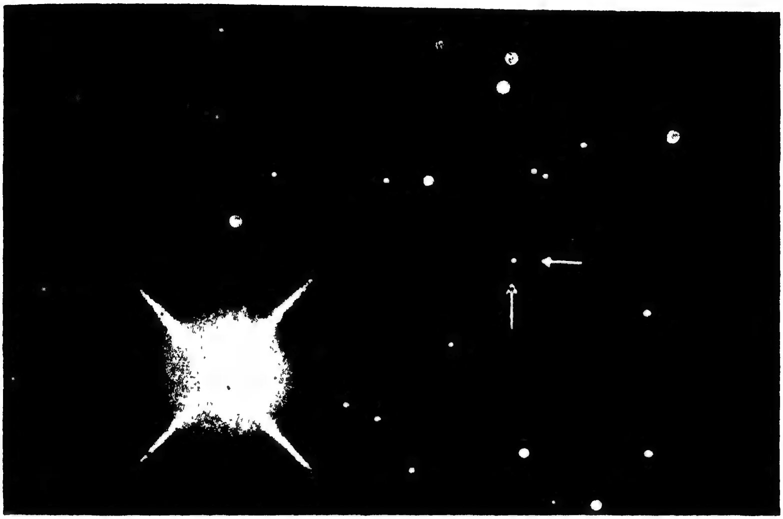
On September 18, Leverrier wrote to Galle, the astronomer of the Observatory in Berlin. They were just then making astronomical charts of the ecliptic there, and hence were well-equipped to track down the intruder. Galle received the letter on the 23rd; it was a clear night and Galle examined the part of the sky referred to, through the Berlin telescope. Within one degree of the place indicated by Leverrier, he that same night found a "star" not occurring on the chart, and which, when further enlarged, appeared as a distinct disk! The new planet was discovered!

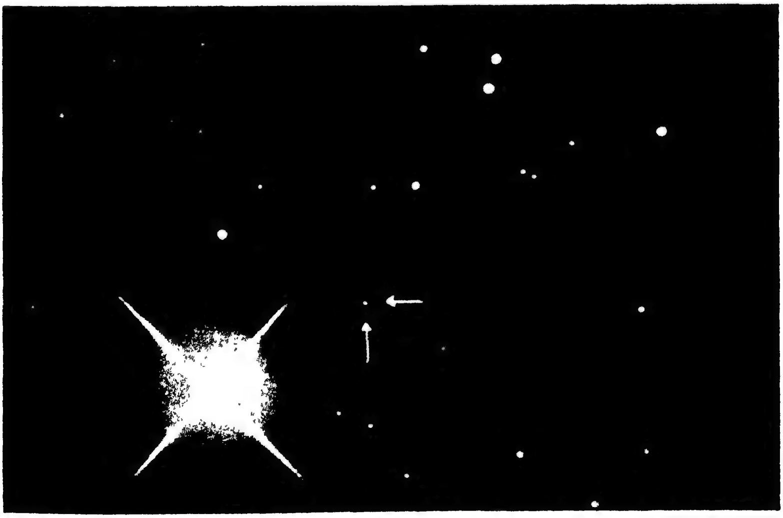
It then transpired that the young English student Adams had worked out this same problem a year before, finding the same solution. He had communicated his results to Airy, who was Astronomer Royal at the time, but the latter had not told anyone anything about it, and had not even taken the trouble to look for the new planet!

Leverrier was a theorist pure and simple. He died without ever having seen Neptune.

Pluto

In January, 1930, the planet Pluto was discovered by the astronomers of the Lowell Observatory in the United States. The facts pertaining to the planet are not yet all known; it has a period of 248 years and a strongly eccentric





THE DISCOVERY OF PLUTO
Photo on March 2 and March 5, 1930.

orbit (eccentricity 0·25); its orbital plane has an inclination of no less than 17° to the ecliptic; its mean distance from the sun is 3,669 million miles. At perihelion it can approach *a little closer* to the sun (and to the Earth) than Neptune. It appears to be considerably smaller than the Earth; certainly not larger. The story of Pluto's discovery is less gloriously triumphant than that of Neptune. Lowell tried to repeat what had been done by Leverrier and Adams. He traced the orbit of Uranus with the greatest precision (Neptune is less suitable as a basis for computation) also accounting for the perturbation caused by Neptune. Still an unexplained, very much smaller, disparity remained. From this he computed the position of the unknown planet, and then he and his assistants searched for it for years. At first in vain. Lowell died (1916) before Pluto was discovered. But at last his assistants found a moving "star" in January, 1930, on two photographs taken of the region of the star δ of Gemini. Careful study of the orbit of this star proved it to be the long-sought planet. But the facts did not tally with the calculations as well as had been hoped.

One can now again put the question, whether Pluto is the last, the very last planet of all in our solar system. And this question can only be answered in the following way: There are reasons (we shall say more about this later) that lead us to believe that, if there is another planet to follow Pluto, this will only be a small one, probably even smaller than Pluto is. From this it will be obvious that, in view of the increasing distance, it will be extremely difficult, if not impossible, to discover such a planet. But, considering the continually improved telescopes and photographic methods, some hope is left.

The Earth as seen from the Planets

We should like to devote a few words to the question as to how the Earth appears to other planets in the heavens, or would appear if there were eyes there that could observe it. This is of importance if we wish to know more about our position and significance in space.

Seen from Venus our Earth is the first outer planet. Its position with regard to Venus is about as that of Mars to the Earth. To Venus it must appear as a lustrous star, more radiant than Sirius, the most brilliant star in the sky. At an opposition of the Earth its diameter in the sky of Venus is no less than 65″, more than one minute of arc. To human eyes it would appear as a tiny disk in the sky! It gives considerably more light than Venus does to us, even at its brightest. For Venus is only a crescent then, whereas the Earth is full at opposition. For some time before and after opposition the Earth seen from Venus, just as Mars does observed from the Earth, appears in approximately three-quarter phases. In the sky of Venus it sometimes retrogrades, just as do the outer planets to the Earth.

And, besides its being so brilliant it is also remarkable in another way. The rotation of the Earth, owing to the variation of the shades of continents and oceans, must be to some extent visible, even to the naked eye. Through a telescope one must be able to perceive the snow- and ice-caps of the Poles and the contours of the Earth as they roll by in 24 hours. And at a distance of at most 35 minutes of arc (a little more than half a degree [1]) a bright "star" must be visible, that revolves round the Earth in some 27 days. Of course our moon! The inhabitants of Venus, if, at least, they exist at all and can look beyond the veil of clouds constantly enveloping the planet, can even see the side of the moon that is always concealed from our view. Now and again they can observe a lunar eclipse and calculate the velocity of light by it. . . .

Seen from Mercury, the Earth appears more or less as it does to Venus, but considerably smaller and less bright. After Venus it is the brightest star in the firmament and has, approximately, the brightness of Jupiter seen from the Earth.

To Mars we appear more or less as Venus does on Earth.

[1] This greatest distance is more than half a degree of arc at opposition. At other positions of the planet Earth it is less. Moreover, at every position of the planet Earth, owing to the revolution of the moon round the Earth, the distance can be much less, down to 0 (occultation or transit).

The Earth is an inner planet with respect to Mars. The greatest distance it can attain from the sun in the sky of Mars is 48°, about as that of, Venus with regard to us. To Mars we are alternately the morning and the evening star; at inferior conjunction the Earth has a diameter of 58 seconds of arc, and shows phases like those of Venus seen from the Earth. The "inhabitants of Mars" also see a bright star accompanying the Earth at the distance of at most half a degree, which is our moon revolving round the Earth and imitating the phases of the Earth on a small scale. They will also be able to see our lunar eclipses quite well and a transit of the moon across the Earth. And it is also an interesting sight when the moon is covered up by the Earth, or when there is a shadow transit.

Viewed from Jupiter, the Earth is an inner planet, just as Mercury is to the Earth. Seen from Jupiter the Earth can never move further than 12° from the sun, which means that it is even more rarely visible to Jupiter than Mercury is to the Earth. If there should be ordinary humans on Jupiter they could scarcely see the Earth or never at all. The best opportunity they would have to do so would be during one of the many solar eclipses occurring on Jupiter, or else during the not very rare transits of the Earth across the sun, when the Earth is silhouetted against the sun as a dark spot, like a transit of Mercury with us. Through a telescope the Earth appears to Jupiter as an evening or morning star, in the shape of a small half-moon.

To Saturn the Earth hardly exists. It can move at most 6° away from the sun, and remains hidden in the immediate vicinity of the sun in the half-light of the dawn and of twilight. Perhaps our existence has become known to Saturn from a transit across the sun.

To the other planets and the rest of the Universe we do not exist at all.

The Asteroids

If you were to study a diagram of the solar system drawn on the correct scale, you would see that between the orbits

of Mars and Jupiter there is, as it were, a gap. This would also appear from the following. There is an old rule, the so-called law of Titius-Bode, by which one can, in a simple manner, remember the approximate proportion of the distances of the planets from the sun.

You start at the figure 3, continually doubling it to get the following series:

3, 6, 12, 24, 48, 96

Then you place a 0 at the beginning:

0, 3, 6, 12, 24, 48, 96

Next, you add 4 to each number:

4, 7, 10, 16, 28, 52, 100

and this gives you the various distances approximately in the right proportion. For, if we take the distance from the Earth to the sun to be 10, the actual distances to the various planets are:

Mercury	Venus	Earth	Mars	Jupiter	Saturn
3·87	7·2	10	15·2	52	95

When Uranus was discovered it proved to fit in fairly well in the series: according to the Titius-Bode law its position should be at 196, and it actually is at 192.

The discovery of Uranus greatly strengthened the faith in the correctness of the law of Titius and emphasized the absence of a planet at about 28. Astronomers redoubled their endeavours to find a planet at this distance. The ecliptic was zealously swept for a moving star; obviously it could not be a big planet, for then it could not have escaped notice for so long. Bode himself founded a society with a membership of 24 astronomers for the purpose of searching for the unknown planet: these efforts met with no success at first, however.

But on the first day of the nineteenth century, the first of January, 1801, Piazzi found a new star in Taurus. The next day the small star proved to have changed its position a little: the new planet was found at last. It proved to be at a distance of 27·7 from the sun (Earth is 10) and so fitted

into Titius-Bode's law perfectly.[1] Piazzi gave the newly-discovered planet the name of *Ceres*. Ceres revolves round the sun in 1,681 days, so more than 4½ years. Its diameter is no more than 480 miles. Under very favourable conditions it can just become visible to the naked eye.

On March 28, 1802 Olbers discovered a second planet, at practically the same distance of 27·7. It proved to have a period of 1,686 days and was given the name of *Pallas*. On September 1, 1804, Harding discovered a third, *Juno*, at a distance of 26·7. On March 29, 1807 Olbers found a fourth, *Vesta* at 23·6. All these small planets are heavenly bodies with diameters of no more than some hundred miles (Pallas 300 miles, Juno 118 miles, Vesta 236 miles.) Vesta is, from the Earth, the brightest. It can sometimes be observed as a faint star in the sky with the naked eye.

And then the flow of discovery of new asteroids stopped. But astronomers, realizing that there must be more, set to work making very accurate celestial charts; with the help of these a moving object such as an asteroid is quickly detected. When this had been accomplished they reaped a rich harvest. In 1845, number five, *Astraia*, came, and since then the discovery of asteroids has been going on continually: there are some astronomers who specialized in finding them and became veritable asteroid-hunters: Palisa found 68, Charlois over 100. Nowadays photographic methods are applied: a photograph is taken through a telescope which follows the apparent motion of the fixed stars; the stars then appear as points, while the asteroids are drawn out by their motion into little lines. Or the other way about: the telescope is made to move with the average rate of the asteroids (the rate at which the asteroids travel through space does not differ materially as they are all about equidistant from the sun), then the stars become little lines and the asteroids points. Altogether about 1,300 asteroids have been discovered. And as the methods

[1] Since then this law has been found to be seriously at fault. Neptune proved to be much nearer than the law allows, and so is Pluto.

are improved this number steadily increases. Those found nowadays are extremely small, their diameter being not much more than 6 miles, or even less. In all likelihood most of them are not even spherical, but just enormous lumps of rock. They are always given some name, and the business of finding names for them all has taxed their discoverers' ingenuity.

The orbits of these asteroids lie for the most part between Mars and Jupiter, but some are strongly eccentric, so that a few describe part of their orbits within that of Mars, and others pass beyond that of Jupiter. Hidalgo, discovered in 1922, extends its orbit even as far as that of Saturn and its mean distance from the sun is even a little larger than that of Jupiter. Eros, observed for the first time in 1898, is very remarkable from our point of view as inhabitants of the Earth. At its perihelion it approaches the orbit of the Earth to within a distance of no more than 13,000,000 miles, so that under very favourable conditions it can also approach the Earth itself to within this distance. This closeness of approach is only exceeded by that of one or two very faint asteroids, with the exception, of course, of our moon. From the time of its discovery Eros has been a source of interest to astronomers; when it approaches the Earth as closely as possible, it is simultaneously observed from two points as far as possible away from each other, and thus, by the method we are now all acquainted with, its distance is determined.

Since the relative distances in the solar system are known very accurately from observations of the periods of the various orbits, it follows that a single measurement of distance between two bodies controlled by the sun, such as the Earth and Eros, gives us all the distances in the solar system, and in particular the distance from the Earth to the sun.

Quite recently, in 1932, two very remarkable asteroids were discovered by Delporte in Uccle and by Reinmuth at Heidelberg. The first (since named Amor) appeared as a star of the ninth magnitude. It proves to be able to approach the Earth to within two-thirds of the distance of Eros,

hence to within 9,000,000 miles, less than forty times the distance of the moon. The second (Cupid) is more noteworthy still. It can come to within one-sixth of the distance of Eros, so to within *no more than ten times the distance of the moon.* Its diameter is probably not much more than half a mile. So the planet is only a lump of rock, an enormous meteor. At its closest to the Earth it appears as a small star of the tenth magnitude. Its orbit is extremely eccentric (0·52?); it can approach Venus to within as little as about 90,000 miles.

The record close approach to the Earth was made in 1936 by a tiny object known as 1936 CA, which was distant only 1,300,000 miles at the time of its closest approach. The orbit of this visitor has not yet been determined with accuracy, so that it is not yet known when it will return to our neighbourhood.

And now we shall take leave of this Lilliputian world. It is almost impossible to get away from the idea that all these minute planets are fragments, as it were, of a large planet destroyed in some "catastrophe."

Comets

What consternation and dismay was caused in olden times by the appearance of a comet! All at once the comet would appear in the sky, frequently in the full blaze of its glory. A brightly shining head or nucleus, with a fiery, lustrous train, sometimes occupying a considerable portion of the whole sky. No wonder that it was regarded as a token of divine wrath and as a herald of dire calamity.

All these ideas have been swept away since the times of Newton and Halley (1656–1742). They showed that comets, just like other heavenly bodies, are subject to the law of gravitation, and Halley soon found that several comets observed in previous times showed so much similarity to each other as regards their paths that they must be fresh appearances of the same comet. Thus, the comet of 1682 proved to be identical with that of 1607 and 1531, and Halley

predicted its return in 1758 or 1759. Several years after his death the comet actually did return, in March, 1759! This fulfilment of his prediction made a profound impression on the world. The comet appeared again in November, 1835, and May, 1910.

From Halley's calculation it was established that the comet (afterwards called Halley's comet) follows a path which has the shape of a greatly elongated ellipse. This ellipse extends to some distance beyond Neptune's orbit. At that point the comet of course travels very slowly (according to Kepler's second law). The nearer it comes to the sun the faster it moves. It returns every 75 years.

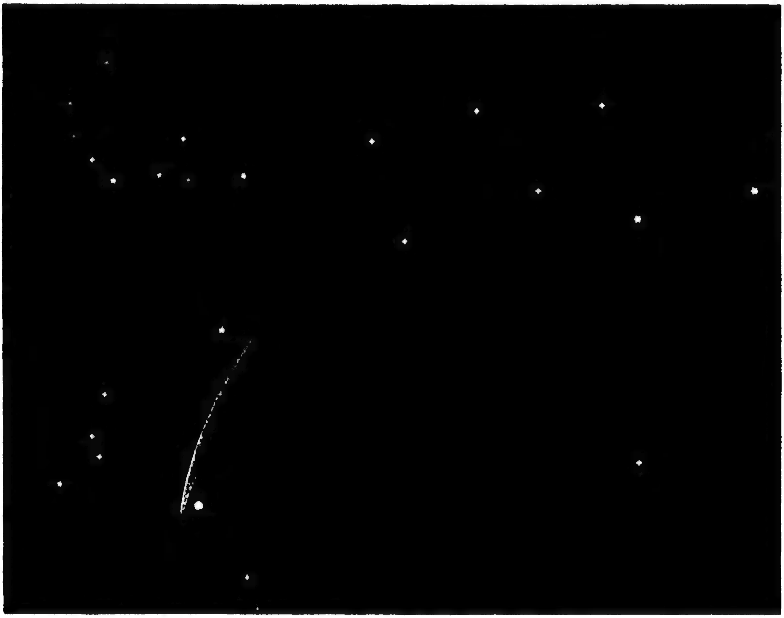
Since then numbers of comets have been discovered, returning at the end of periods of varying length (periodic comets). Most of them are of no particular significance and can only be observed through a telescope.

It was formerly held that comets came to us from the depths of Space, shot round the sun and then vanished back into infinite space for good, unless their orbits were so changed by perturbations that they became ellipses and from that time belonged to the solar system. This, according to theories of olden times, turned the comet into a periodic comet, which would thenceforth at certain periods of varying length return to the vicinity of the sun and then be visible to Earth for some time. Those comets were then "adopted children" of the sun. Nowadays, from considerations that cannot be explained in brief, it is held that all comets travel along elliptical orbits. But some are greatly elongated[1] and then the comets only return at the end of several centuries. It is often very difficult to predict exactly when they will return; their orbits undergo severe perturbation by the gravitational force of the planets, especially of the larger ones, such as Jupiter and Saturn, so that the precise

[1] In the last few years some comets have been discovered whose orbits are but slightly elongated, so that they can be watched for a long time. One even is now known whose entire orbit lies within those of Jupiter and Saturn. This comet (Schwassmann-Wachmann I) was observed in July, 1933, at its aphelion. This had never before happened with a comet. It will probably remain permanently visible.

moment of their return is subject to great variation. If the velocity of the comet in its orbit becomes smaller, its orbit becomes shorter.

Thus the comet can gradually—sometimes in the course of centuries, sometimes in a much shorter period—acquire a much less elongated orbit. One of the major planets, Jupiter, Saturn, Uranus, or Neptune, may gain such pre-



Donati's Comet in 1858.
After G. P. Bond, Cambridge, Mass.

dominating influence on its orbit that the point at which the comet is as far as possible away from the sun, remains in the vicinity of one of those planets. Then—within certain limits—its condition gains a certain permanence and the comet, at least for the time being, becomes a really periodic comet. Thus the Jupiter comets have periods of 5 to 8 years, the Saturn comets of about 13 years, the Uranus comets of about 33 years, and the Neptune comets of about 73 years.

So you see that Halley's famous comet must be a Neptune comet.

But the opposite may happen, too; the speed of a comet in its orbit can increase by the gravitational force of the planets; thus a really periodic comet can even lose its normal periodicity and not return when expected. All this is very difficult, or even impossible, to calculate beforehand.

Although the science of comets has made great progress during recent years, much is left that is unexplained. It is an established fact that the head of the comet is the actual comet itself; the tail, or train, is not developed until the comet approaches close to the sun, when it is awakened, as it were, from its slumbers by the heat of the sun. Frequently, the formation of the tail is not, or hardly, affected at all. The comet then shows in a telescope as a vague nebulous spot. Even the head, the actual comet, is very tenuous, often even incredibly so. The dimensions of the head are very large, but yet it exerts no perceptible influence on any other heavenly body. Near the sun it is often, as we mentioned above, roused to great activity; luminous cometary matter begins to stream from the head; thus a tail, occasionally more than one tail, is formed. This points away from the sun; apparently what is known as the radiation pressure repels these fine particles of matter. It has long been known and proved in our laboratories that rays of light exert perceptible and measurable pressure upon very minute particles of matter. The faintly bent shape of the tail is accounted for by the motion of the comet and this radiation pressure. So the comet comes from the depths of space and as it approaches the Earth it can be observed through large telescopes as a small nebulous mass. But sometimes astronomers are less fortunate; for then the comet gets quite close to the sun and then it is very difficult, or even impossible to see it, until, after having passed perihelion (the point in its orbit when it is closest to the sun), it all at once appears in the sky with a well-developed train. That is why comets can turn up so suddenly. To-day, to-

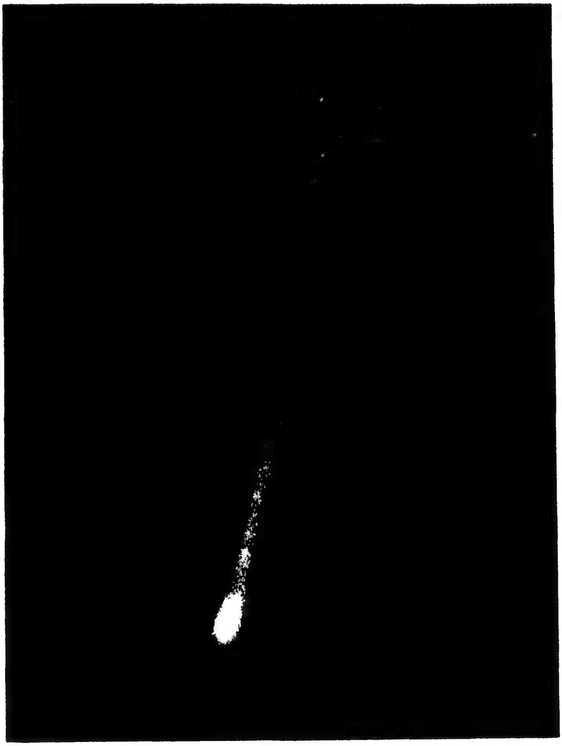
morrow, any day a fine comet, visible to everybody, may suddenly appear in the heavens.

It appears that most comets, owing to the outflow of cometary matter, lose in force and gradually peter out. (But on the other hand it is quite conceivable that others on their journey through the solar system manage to accumulate new matter.) The cometary matter ejected remains in, or very near, the comet's orbit; it must proceed to move round the sun, approximately in the comet's orbit. We shall see presently what becomes of this cometary matter.

Many fantastic things have been said and written about the possibility and the dangers of a collision between the Earth and some comet. The end of the world has even been predicted in this connection. But the risk of such a collision is extremely slight; in all likelihood the consequences of such a happening would not be very serious either—it is even conceivable that the Earth might pass through the head of a comet without the inhabitants even noticing anything very particular. There might be a shower of meteors. But the comet is so finely dispersed that the collision would scarcely deserve that name. The following facts serve to illustrate how rarefied a comet is. A star shines just as bright, undergoing no change whatever, through the head of a comet. When Halley's comet passed across the face of the sun in 1910, it was utterly invisible. Indeed, the average density of a comet is apparently not more than $\frac{1}{250000}$ of that of the air!

We should like to say a few more words about the reappearance of Halley's comet in 1910. Naturally, the periodicals and papers of the latter part of 1909 continually drew attention to Halley's comet and its approaching return. In the autumn it was even reported that it had already been observed through the largest telescopes. Numbers of people looked forward with great excitement to seeing it with the naked eye, and it was expected about May, 1910. Then all at once, in January, there was the comet in the sky in full glory, gaining in brilliance night after night, with a

magnificent train! The general public unhesitatingly identified it as Halley's comet. But it was not; it could not possibly be. An impostor had taken the place of the comet in order to be the recipient of the cordial welcome of the inhabitants of the Earth intended for Halley's comet.



THE COMET 1892 I.

And the usurper succeeded in doing this—nearly every middle-aged and older Englishman will tell you in all honesty that he saw Halley's famous comet with his own eyes in 1910, and that it was a wonderful sight in the sky.

And comet 1910 A was indeed a wonderful sight, the first for many decades. There has been none like it since to compare with it. I saw it myself, many times; one night

I watched it when there was snow lying on the ground and the stars were glittering from a cloudless sky; the head had just reached the horizon—and I could follow the tail up to the Zenith!

And what about Halley's comet? Poor thing! After the triumphant appearance of the impostor, it could not have been unluckier. It eventually arrived when the days were almost at their longest in our country, and when twilight lingered long. After many vain attempts I at last got one glimpse of it, as far away as possible from the lights of the town, fairly close to the horizon: it was a faintly luminous cloud of vapour, without a trace of a tail. Not one in a hundred Englishmen saw Halley's comet in 1910. But ask anybody you like—and they will still wax enthusiastic about the magnificent comet of Halley that they saw in January, 1910!

But, in all fairness to Halley's comet, we may not omit saying that in other regions of the Earth, where conditions were more conducive to visibility, the comet was seen very finely. For instance in India it is said to have been a splendid spectacle, with a train from the horizon to the Zenith.

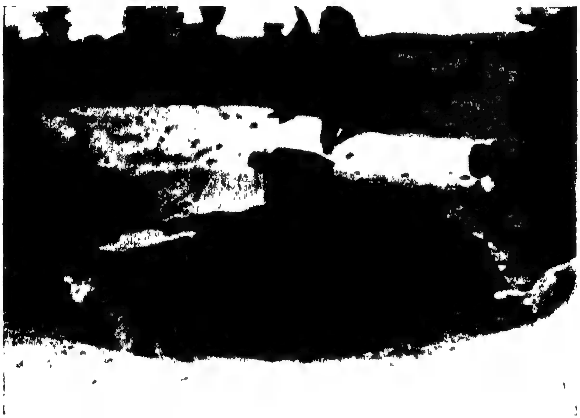
Shooting Stars and Meteors

Every one of my readers will at one time or another have seen a shooting or falling star. And many people think that then in some way or other a star has actually got loose from the vault of heaven and has hence dropped. A person who affirms this in all seriousness proves he has not gained the slightest inkling of astronomical matters. For we all know that there is no vault of heaven to which the stars are fixed: so of course they cannot work loose, and if they did they would certainly not fall to the Earth. And the stars are so immensely far away that they can travel at tremendous rates for thousands and tens of thousands of years, without our being able to perceive that they have moved at all, at least not with the naked eye.

So a shooting star is certainly no star; but what is it? It is not difficult to answer this question. Bright shooting stars draw great attention and there are always observers who have carefully watched the path they travel and have mapped it out. If, now, two observers at a distance of some twenty or thirty miles from each other, or even a few hundred miles, have done this, it transpires that its path appeared to be quite different at one spot from what it was at the other. From this difference it is possible to calculate the height of the shooting star. The point at which the shooting star becomes visible then proves to lie in the very highest strata of the Earth's atmosphere, 90 to 110 miles high. This makes the nature of the shooting star clear to us: it is nothing but a small stone that penetrates the Earth's atmosphere at a terrific rate—more than 60 miles a second. Although the outer layers of the atmosphere are extremely rarefied, the stone's speed is so high that friction with the atmosphere makes it glow and become visible. Even minute glowing particles of matter can appear as shooting stars on a moonless night. At the end of some moments they evaporate completely. The stones thus entering our atmosphere are of varying sizes; the larger ones appear as bright shooting stars; these lose glowing drops or particles in our atmosphere, which fragments, by the greater resistance of the air, remain behind and cool down slowly, owing to which phenomenon the path of the parent meteor remains visible for some moments by a faintly luminous streak across the sky. Those larger still, brightly illuminate their surroundings at night: they are called fire-balls. And the largest of all reach the Earth as meteorites. Of course most of them drop into the sea, and, unless some ship happens to be near, then nobody ever hears anything of them. Others again come to Earth in uninhabited regions. And then, too, they are not noticed, unless it happens to be a particularly large meteorite, which is found later and recognized as such. Altogether about a thousand meteorites have been found and identified.

The arrival of a meteorite on Earth, be it large or small,

is a tremendous event for the immediate vicinity. At night the whole region round is illuminated, sometimes *more* brightly *than by daylight*, by the meteor that shoots down in a slanting direction. Even if it happens in the daytime it appears as a dazzling ball. This is accompanied by deafening explosions, like a heavy thunderstorm. Then the meteorite strikes the ground, usually only making quite a small hole in the ground. The meteorite itself varies in size: it may be as small as a pebble or as large as a boulder, in exceptional cases it is even larger. There are some weighing as much as 60 tons.



METEOR, HOBA, S.W. AFRICA
Photo: Schneiderhöhn

But even quite a small stone can during its fall push an enormous ball of fire, with a diameter of some hundreds of yards, in front of it. Consider the tremendous rate at which the stone enters the atmosphere. It presses together the air before it, heats it to an extremely high temperature, and this compressed, red-hot mass of air appears to us as a large, glowing ball. The resistance of the air greatly reduces the speed of the meteorite; when it reaches the Earth it no longer travels with exceptional velocity. The stone on Earth, even immediately upon its fall, is not so hot as may be supposed. Apparently it scarcely has time to get really hot inside (from the extreme cold of space).

Every year an average of only about five new meteorites can be scientifically examined. And yet the number that reach the Earth every year would appear to be as much as 10,000, by reliable calculation. The yearly number of shooting stars must be far more.

Meteors can be divided into two main kinds: stone meteors and iron meteors. The latter consist chiefly of iron.

Of recent years meteorites found have been carefully tested to find their composition and the age of their stone. It has appeared that practically all the elements occurring on Earth may be found in meteorites, too. The most usual are: iron, oxygen, silicon, magnesium, nickel, sulphur, calcium, aluminium, sodium, chromium, cobalt, potassium, manganese, titanium and phosphorus. The age of meteors has also been determined by modern methods, by which the age of geological strata on Earth is also determined (finding the contents of uranium, thorium, helium and lead [1]). This proves to be from a hundred million to 3,000 million years. This is very important, as the age of the oldest stones on Earth is of the same order of magnitude, that is, about 1,500 million years. This is an indication that meteors are of about the same age as our solar system. If they came from space beyond the solar system they would probably be much older, for reasons that we shall deal with later on.

During certain times of the year many shooting stars are observed on moonless nights. The Perseids (August 10–13) and the Leonids (November 14–16) are particularly well known. The Perseids, in particular, are very suited to good observation: many people are then on their holidays!

[1] The content of uranium and lead is of special importance in this connection. Uranium is a radioactive element, which very, very slowly converts itself into other elements, taking an immensely long time to complete this process. There is nothing in the world that can retard or accelerate this process. One of the final products is lead, but a kind of lead that is not quite like ordinary lead in every respect. From the proportion of uranium and uranium-lead contained in the stone, the age of the latter, that is, the time that has passed since it solidified to actual stone, can be calculated with great accuracy. This uranium "clock" is reliable to a degree, it never gains or loses.

So, then, the Earth appears to traverse an orbit of particles of matter every year. The Italian astronomer Schiaparelli succeeded in calculating the path of these minute bodies in the solar system from the path of the Perseids in our sky. This proved to coincide with that of a famous comet (1862 III). He then made the same calculation with respect to the Leonids. The orbit of these proved to coincide with that of the Uranus comet (1866 I). We observed that Uranus comets have a period of 33 years; well, every 33 years the Leonid meteors appear as a dense meteor shower. This solves our puzzle: the swarms of shooting stars are cometary matter, ejected by comets and left behind in their orbits. At one point of the orbit it accumulates, but gradually it spreads over the whole orbit. Every year, when the Earth passes through this meteoric orbit, numerous shooting stars appear, but after a number of years, concordant with the comet's period of revolution, there is a veritable "meteor shower." But here again one must be careful in making predictions. Thus the last Leonid shower, which was expected about 1933, never put in an appearance. The orbits of these small, drifting particles are disturbed—probably even in a stronger degree than those of the comets—by the large planets.

On October 9, 1933, a very fine meteor shower appeared on the continent of Europe. Thousands of meteors were counted within a few hours. This phenomenon had not occurred in Western Europe for half a century. Again it transpired from calculations that there was a comet behind it, this time Giacobini's comet, which has a period of from 6 to 7 years. It appeared afterwards that an English astronomer, 7 years earlier, had predicted a meteor shower to come on October 10, 1926, in connection with the comet. So, in a way, this phenomenon was not quite unexpected. Therefore it is not impossible that it will be repeated on October 9 or 10, 1940, at the end of another 7 years. But one must bear in mind the many difficulties in predicting occurrences concerning comets, and also that a meteor shower is quite invisible if it happens to fall in the daytime!

The abnormal Twilight in 1908 and the great Siberian Meteorite

On June 30, 1908, a very remarkable phenomenon occurred in this country. It was midsummer and so the days were long. In our country, from the beginning of June to half-way through July, twilight gradually passes into dawn: it is never quite night in those weeks. At midnight (1 o'clock Summer Time) on a clear, moonless night one can still see a faint glimmer on the Northern horizon, especially if one is far from the lights of a town in a large

The trees are lying like matches dropped from a box, struck by the force of the huge Siberian Meteor.

Photo Kulik (Ninenger, Our Stone-pelted Planet)

open space. Even as far South as Southern England we sometimes enjoy faint glimmerings of the midnight sun! The highest strata of the atmosphere spread a little sunlight to our latitudes. It is not entirely dark until the sun is 18° below the horizon; round about June 21, it is in this country no more than about 15° below the horizon, near London. So there is nothing peculiar in the fact that it was not quite dark on that memorable day of June 30, 1908, at 11 o'clock at night. But it was light, as light as it is at most half an hour after sundown! And it *remained* as light as that all night.

I can vividly remember that night. I was at home and had noticed nothing particular. But at 11 o'clock I went up to my bedroom, which happened to face North. I stood before the window looking out in amazement. There was still strong daylight. And it was 11 o'clock at night, by actually solar time, for Summer Time had not yet been introduced. I looked out and saw that the Northern sky was entirely illuminated, I saw the red glow of sunset on the horizon. For a moment I thought it was the aurora borealis, but then at once rejected this thought. No, it could not possibly be that; that was twilight, but now the Northern sky looked as the North-Western sky usually looks at 9 o'clock at this time of the year.

I quickly called a friend and together we went out to explore. We walked up a hill from where we could see the whole sweep of the Northern sky. By now it was half-past eleven, but still the Northern horizon was in the red glow of evening and the whole of the sky to the North shone yellow. The phenomenon persisted like this, gradually passing to the East. At midnight it was only necessary to light up to comply with regulations. Towards 1 o'clock it grew distinctly lighter—I saw very light nebular clouds right up to the zenith. They reflected a pale light. Soon after, the new day broke.

The next night brought a repetition of the phenomenon, in a somewhat slighter degree. On July 2 the sky was quite overcast at night.

In the morning of this June 30, 1908, the greatest cosmic catastrophe that has ever happened to the Earth in historic times had taken place.

In Central Siberia, at about 60° Latitude N. and 101° Longitude E. a gigantic meteorite had come to Earth. Its exact dimensions are not known; evidently it penetrated deep into the ground; the fragments could not be found. But a number of craters were found whose diameters were from 30 to 150 feet, in which the fragments of the meteorite had apparently disappeared. This crater area is the centre

of a region that was totally destroyed. Round the craters there is a circular region in which all the trees were entirely burnt away. Round this again, there is a zone, from 7 to 12 miles wide, where the trees were left upright like telegraph poles, but stripped of their branches and leaves. Then comes a third zone 18 to 24 miles wide, in which all the trees were felled radially towards the outside (*see* illustration, p. 239). This totally devastated region has an area of about 450 square miles. Beyond this it gradually passes into normal forest.

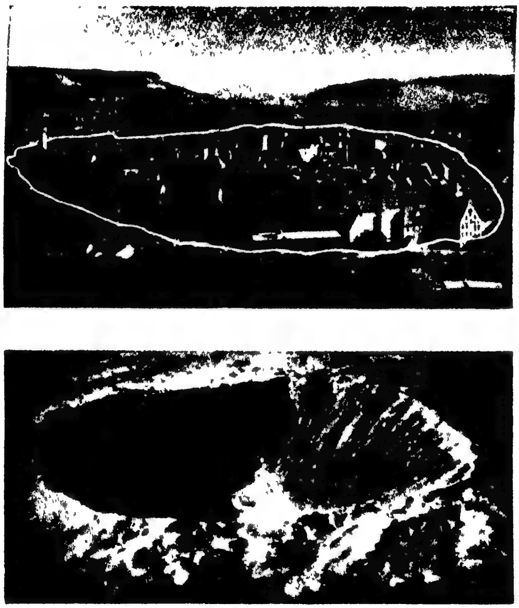
I called the fall of this meteorite the greatest cosmic catastrophe that ever happened to the Earth within historic times. The meteorite fell in a practically uninhabited area. About 50 miles away there is the trading station Vanovara. All the windows there were smashed and the doors torn from their hinges. The mean hovels of the Tunguses were upset, herds of reindeer fled from the spot. Thousands of reindeer appear to have perished. It is not certain whether any human beings were killed. In those regions a few lives more or less are of little account.

It took a long time for rumours of this calamity to penetrate to the civilized world. The Soviet Government many years later equipped several expeditions and they managed to find the spot where the meteorite had landed. Then the date was established as exactly as possible by local enquiry; moreover, at the time that the meteorite must have struck the Earth, a slight earthquake was registered by Russian seismographs and even at Jena. And the barometer proved to have shown abnormal deflections owing to the wave of air caused by the fall. Thus the date could be determined with absolute certainty: the early morning of June 30, 1908.

As soon as I read of the results of this expedition and the exact date in the papers, I was reminded of that remarkable night, the date of which I had noted. Could there be some connection between these events? Could not this immense meteorite have left a trail of cosmic matter very high up in the

atmosphere, that had caused the extraordinary twilight by acting as a kind of mirror?[1] I thought this must be so.

And, indeed, it was. Careful investigations concerning the beginning of the extraordinary twilight phenomenon showed that the clouds of cosmic matter had first appeared above Russia, then over Central Europe and finally over Western Europe. Probably at 10 o'clock that night there



The huge meteor-crater at Cañon Diablo, Arizona, U.S.A. Diameter 1,300 yards. Depth 570 feet. Above, the circumference of the crater, drawn on a photograph of a modern city (Jena) to show its extent.
Photo: C. Zeiss

was nothing remarkable to be noticed in our country. So the clouds of cosmic matter came from the East, from Siberia, and the connection between the two events may be regarded as proven. What a fortunate thing that the meteorite fell in such a desolate part of the world. A city like London, or Paris, would in all likelihood have been practically com-

[1] Cosmic matter itself can reflect sunlight, or else water-vapour can condense on these particles of matter as nuclei, so that, at quite abnormal altitudes, real, reflecting clouds can be formed.

pletely destroyed if such a calamity should have happened there. Millions of human lives would have been lost. Probably the Earth was visited by such catastrophes in prehistoric times as well. Only one large crater used to be known that was certainly caused by such a meteorite: the crater of Cañon Diablo in Arizona (U.S.A.), about 4,000 feet across and 570 feet deep (*see* illustrations on opposite page). In the last few years nine more of such craters have been found scattered over the whole Earth (this includes the one in Siberia described above). Such a phenomenon is the other extreme of the scale: at one end the glowing particle of cometary matter, at the other the gigantic meteorite many hundreds of feet in diameter! In the case of such a body, an untrained person really would have cause to believe in a falling star.

The Zodiacal Light

In the tropics, where the ecliptic is nearly always steep and sometimes perpendicular to the horizon, on clear, moonless nights, shortly after sunset or just before sunrise, one can sometimes see a column, or rather a pyramid, of hazy light, with its base on the horizon, more or less in the ecliptic, thus in the zodiac. In this country, too, the faint light is visible when conditions are in every way favourable, thus when the ecliptic is steep upon the horizon, either just after sunset, or just before sunrise. This is the case just after sunset about March 1, a few weeks before the vernal equinox; just before sunrise some weeks after the autumnal equinox, in October. Then the angle of inclination of the ecliptic upon the horizon is large, at its greatest $61\frac{1}{2}°$, in the neighbourhood of London.

So if you wish to watch the zodiacal light here (and of course it is most convenient to watch it in the evening and not before dawn), it is best to choose a date between February 1 and April 1, preferably as near as possible to March 1, about an hour and a half after sundown. Then, if the weather is fine, and there is no moon, nor a town near, one

has at least the *chance* of seeing the zodiacal light. In town, though I have repeatedly tried to do so, I have never been able to see it.

In the tropics under very favourable conditions a fainter glow of light may be visible by the side of and above the main pyramid, and this may even remain visible as a dim band of light the whole night through. This band of light gains in brightness at the point of the zodiac just opposite the sun. This bright part is called the "counter-glow." It would appear that this counter-glow is also visible in the British Isles occasionally under very special circumstances. It will not be difficult for enthusiasts to *look for* it—in the zodiac, exactly opposite the sun. But one must avoid the months when this light coincides with the light of the Milky Way: i.e. June and December.

The exact cause and the nature of the zodiacal light and the counter-glow are not known with absolute certainty. But it is highly probable that in and near the ecliptic fine particles of matter turn about the sun. So, according to this theory, we see these illuminated particles as the zodiacal light. And the counter-glow would seem to indicate that these particles extend even as far as beyond the Earth's orbit.

It is quite certain that the zodiacal light is not an atmospheric, but a cosmic phenomenon. In all probability it reveals the existence of small particles belonging to the solar system. That is why it is given a place here.

Solar and Lunar Rainbows

We may add a word here about phenomena that do *not* belong here at all, just to stress the fact that they do not. We need not explain the *rainbow;* readers know this phenomenon and what causes it, and also know that it is not cosmic. It lies beyond the scope of astronomy. So we need say no more about sun and moon rainbows.[1]

[1] The reader should try to find a moon rainbow, when the moon is shining bright, not too high in the sky, and it is raining—once I saw a very fine example.

Haloes

Haloes round the sun and moon do not belong to astronomy either. They are rings round the sun or moon. Sometimes they are very beautiful—the inner part of a moon halo sometimes appears to form a large dark disk in the sky. Haloes can sometimes also be enhanced by a second ring, by tangential curves, by "mock suns" or "mock moons," by a column rising from the sun or moon to the ring. Haloes in all these stages can be very beautiful. The beholder may think and often does think that he is watching some cosmic phenomenon. But that is not the case. Haloes are occurrences in our atmosphere caused by refraction of the light of the sun or the moon in ice crystals drifting in high strata of the atmosphere. The effects observed can be explained down to the smallest detail from the properties and shapes of these crystals. Have a good look at a halo, if you should happen to see one, but remember that it is a terrestrial phenomenon, just as the rainbow is.

CHAPTER VII

A VISIT TO MARS

SOME time ago a man, an inhabitant of the Earth, succeeded in reaching Mars by rocket. He remained there a few years and evidently managed to keep alive, thanks to his good equipment and a large stock of provisions. Then he returned. Upon landing, his rocket crashed and was burnt up; the occupant was killed. Most of his diary was also lost in the flames; but just a few fragments, some pages, were miraculously spared. These pages contain a number of important facts, all about conditions on the planet. They almost entirely confirm the results of the marvellous research made of late years by numbers of scientists concerning the temperature, atmosphere, moisture, the polar caps and the vegetation on Mars. From certain passages it is evident that our traveller was not a very keen observer; so his information must not be regarded as absolutely accurate on every point. But, taken generally, his notes create a reliable impression; [1] it is more than a pity that the rest of them were lost. Then we might have learnt something more about the peculiarities of the various regions of the planet, about its remarkable vegetation, or whether he ever saw any animals there. From certain passages it would seem as though he had referred to these subjects in earlier parts of his diary. As it is, we must be grateful that what pages we have were not burnt with the rest.

October 43.[2] It is almost midnight and most bitterly cold.

[1] Thus his information about the Martian celestial phenomena largely corresponds with what Flammarion calculated, and communicated in his *Les Terres du Ciel*.

[2] How he divides his calendar is given at a later date.

In the tropics of this blessed planet too! And to think that we are now in proportion close to the sun; very shortly we shall have reached perihelion. That means a kind of extra summer. The heat we now receive from the sun is almost as much as 1½ times as great as at aphelion. And yet the thermometer reads $-80°$ Fahrenheit. In these tropical regions I observed at aphelion temperatures even 45° lower, at midnight.

Everything round me is now covered with a thin coat of hoar-frost; this includes the plants here in the plain, about which I wrote at length some days ago.[1] I am sure that the plants possess some mechanism by which they manage to absorb moisture. But my knowledge of biology or physics is too scant to enable me to understand how they can possibly do this at such a low temperature.

It is a perfect night. As the reader of this diary knows, it is nearly always cloudless here. It is only occasionally that rather thin, high clouds are visible. But of late it has been fairly damp, for this part of the Universe! The sandy ground is not so dry as it sometimes can be; we have for a long time not had any sandstorms, which entirely blot out the horizon by yellowish-brown clouds of dust.

All the dust in the air has settled and the atmosphere is exceptionally pure.

I have not yet given a description of our sky at night, so I can do that now. Oh, I can gaze up at it at night for hours. Then I can fancy myself back on Earth for a moment. I see all the familiar constellations and stars. Look, there is the Eagle, there is Antares. And all my other old friends. How I wish I had never set out for this dry, barren land. To-night the Earth was not in the sky, I have not seen it for a long time, it must be about in conjunction with the sun now. I cannot see it now in the daytime either, whereas, as long as it is not too close to the sun, the Earth is also visible to the naked eye during the day against the deep-blue Martian sky. Some weeks ago I

[1] This was unfortunately destroyed.

saw it last, as an evening star; since then it has been lost in the twilight. What feelings I had as I watched it through my telescope! As I saw first of all Eastern Europe, then Western Europe appearing on its crescent! As I saw it rotating on its axis in 23 hours and 20 minutes,[1] turned a little farther every night! As I watched the fine crescent of the moon (the *real* moon, I mean) travelling round it at night! A feeling of melancholy, of infinite longing, then possessed me. How I should like to go back there again! Back to the place where I belong, to which I am linked by a hundred bonds. Back to Mother Earth. But now she is not there. I hope to see her again soon, when, as a morning star, she escapes from the dawn.

What a perfect night! The stars shine steadily in the inky-black sky. I have seldom seen them as bright as this on Earth. There goes a meteor! Yes, I see them oftener here than one does on Earth. And it is no wonder in this clear sky. Perhaps also there are more particles of cosmic matter near the orbit of Mars. The Milky Way is of an almost dazzling beauty.

It seems to be getting a little lighter in the Western sky. Look, there comes Phobos, our large moon, rising rapidly from the horizon! In nearly 5½ hours it travels—in the wrong direction—from West to East! It is very odd when sometimes it pops up just after sunset in the very place where the sun went down. It is our moon, our big moon too! What a poor sort of moon it is! A small disk with a diameter of some 8 or 9 minutes of arc, and as much as that only when it is at its zenith in the sky, so when it is at its largest to our view. Even then its diameter is less than a third of the real moon. Its surface is less than a twelfth of the surface of the latter; its light perhaps a thirtieth. And only when it is full and not eclipsed. At present it is in its first quarter; the lower half illuminated. You can almost *see* it growing from here. In about an hour and a half it will be full. Then there is sure to be a total eclipse

[1] For the way in which our observer records his time, *see* page 255.

again, which usually lasts about half an hour. You then scan the heavens for it in vain. Only just before the end of totality it reappears, faintly reddish. Less than 5½ hours after its rising it sets again in the East.

We have another moon, too, called Deimos. But really, it scarcely deserves to be called a moon at all. Its diameter is less than a quarter of that of Phobos; it gives no more than $\frac{1}{16}$ of its light. And it remains below the horizon for almost three whole days. But at least it does rise properly in the East. There it is, actually rising at this moment. The lower half is illumined too, but that in its case means last quarter. Deimos rises slowly in the sky. When presently, in about 5 hours, the sun rises again, it will be less than 15° up in the sky. Then its crescent will have become very thin. For, just over an hour after, the sun will have caught up with it, and it will be "new" Deimos.

It is an ideal place for lovers of lunar eclipses. When it is full moon, Phobos is very often eclipsed. And Phobos's next full moon follows as soon as 7½ hours after the last. There one can sometimes see two total eclipses of Phobos in the course of one night. I have seen that more than once myself. And that is not all. We have got Deimos too. That travels from East to West in 64 hours, so remains almost three whole days above the horizon, and can during that period be full three times and also be eclipsed three times. But of course that does not happen in one night. In one night you *can* see three eclipses, but then two are of Phobos and one of Deimos.

And finally there is a very particular kind of eclipse here unknown to us on Earth, I mean of one moon by the other. In at most about 10 seconds Phobos passes across Deimos, usually covering it up completely. This can happen in the most diverse phases. So there's plenty to be seen here as regards eclipses.

October 44. The sun is rising. A beautiful dawn, the same as on Earth. It certainly is perishingly cold. The thermometer

registers 22° F. below zero. But yet the hoar-frost at once evaporates in this dry air from the ground and from the plants. The sun ascends into the sky. It is getting perceptibly warmer. The solar disk is certainly much smaller here than on Earth, not much more than 20 minutes of arc, but I am in the tropics, it is not very long since the equinox, and the sun rises almost straight up into the sky. Besides—it is near perihelion. So its rays are as strong as they can be here.

Towards noon the sandy soil has actually reached a temperature of 75° F. The air is much colder than that; quite close to the ground it is nice and warm, but some yards from the ground it is scarcely above freezing-point.

I walk up a little hill rising from the wide plain. It is still a peculiar sensation, even after years, to dance lightly up a slope owing to the low gravitation here. Up here I have a fine view. The plain below with its cactus-like plants stretches away to the horizon. Everything in it has the same almost uniform greyish-greenish blue colour. It is now the best time of the year for the plants: the short while that they can flourish. Little as it is, there is now at least some moisture in the air. The large polar cap at the South Pole, where the vapour in the atmosphere condenses as a thin film of hoar-frost, is now, more than a month after the equinox, evaporating quickly as a result of the rise in temperature. The whole atmosphere of the planet is getting moister.

But that will not last long. The South Pole is approaching a perihelion summer. Very soon the greater part of the vast polar cap will have evaporated—less and less water vapour will be absorbed by the atmosphere, while the North Pole cap is already growing at the approach of winter and the liberated water vapour is already beginning to be fixed there. Our plants will now, as at every perihelion, have a particularly difficult battle to fight: towards the end of January, a month after the summer solstice of the Southern hemisphere, the South Pole cap will have disappeared entirely,

then the atmosphere will be drier than dry and the sun's almost perpendicular rays will pour their scorching heat on our poor, withering plants in the afternoons. And soon they will have shrivelled up this whole plain and give it a withered, purplish-red look. Only in the middle of the plain, where it dips down and where the plants are rather more sheltered, will they be able to keep fresh a little longer. But the plants themselves do not die. A better time comes for them again towards April. But in February everything looks dead. Then the wind blows the yellow-brown desert sand about. It is then wild and desolate here.

October 45. It was again very fine to-day. And from an astronomical point of view it was a very remarkable day. It was amazing, I was dumbfounded. I shall never forget the sensation.

But I must try to put things down in an orderly fashion, as one should do in a proper diary. To continue, the sun was again shining brightly in the sky, as it nearly always does here. I happened to be watching it through my telescope. A fine group of sun-spots was visible. Then a small solar eclipse started. There was nothing peculiar in that. We see some 1,400 eclipses here every year caused by Phobos, and about 130 by Deimos. A day without an eclipse would therefore be more remarkable than a day with one. Besides, a solar eclipse here is not very interesting. It is never total; the eclipses caused by Phobos are usually not annular, those caused by Deimos in most cases *are* annular. Phobos manages sometimes to cover up about $\frac{1}{8}$ of the sun with its black disk, but such an annular solar eclipse, if it happens high up in the sky and Phobos is at its largest, only lasts at most ten seconds; low in the sky, the annular eclipses may sometimes last at most eighteen seconds. Deimos can be completely observed on the face of the sun during a minute and a half; the difference between these maximums, with the "moon" in a high position or a low, is in ratio less in the case of Deimos than of Phobos.

Deimos can never cover up more than about one per cent. of the disk of the sun. To-day, I in the first place had the privilege of seeing a compound solar eclipse. These are quite rare. Exactly at the moment when Deimos was half-way on its passage across the sun, Phobos shot across it, for some seconds covering both Deimos and part of the sun. This alone would have been sufficient to make the day a very special one for me from an astronomical point of view. But a far more remarkable thing was to present itself to my eyes. As I was watching the sun through my telescope, I saw a very small black body appear at the edge of the solar disk; some minutes passed before it was silhouetted in its entirety against the sun. It could not be Venus; I had seen Venus last night shining as the evening star in the Western sky! Then it must be Mercury?

At first sight this tallied rather well with the dimensions it should have. The black spot slowly travelled farther in its course across the sun. I followed it with great attention. To my great surprise a much larger disk appeared after some time at the edge of the sun, and this disk required even longer to make its full appearance against the sun. Then suddenly, with a shock, I realized what they were; how could I have been so stupid as not to understand at once! For I knew that the Earth was at inferior conjunction, so I should have realized that a transit of the Earth across the sun was at least possible. Indeed I was right, it was the Earth and the moon outlined against the sun!

A rare sight, which I had the good luck to witness, and which only happens twice in a century on Mars. On they travelled, very slowly. The Earth with all its strife, its feuds, its pride, as a small, very dark spot passing in front of the solar disk.

December 34. I am now on the edge of the South Pole cap. It is about summer solstice. Not very much is left of the polar cap. Three, four months ago it extended as far as 60° Lat. (S.). At this time of the year only a small part

of it is not evaporated by the heat of the sun. As soon as the temperature rises to -60° F. the hoar-frost on the ground evaporates. I have repeatedly been able to check this statement with my thermometer. Towards the South as far as the eye can see the whole plain is still white. It is entirely coated with a film of hoar-frost only a few millimetres thick. At times when the sun burns down on it tracts about 60 miles wide can evaporate and disappear in one day.

There is no liquid water to be seen anywhere. No rain ever falls here or anywhere else on the planet, nor a particle of hail or a flake of snow. Hoar-frost is the only form of precipitation there is, everywhere, even in the tropics, and it settles as a thin coat in the night, if the atmosphere is not too dry, particularly during the long winter at and near the Poles, especially in the Southern hemisphere where the winter is longer and colder. But never any rain, never snow. Liquid water does not exist here. In all my wanderings up and down the planet I have never come across a stream, or a river, a pool, a lake or a sea. I have had the greatest difficulty in preparing sufficient drinking water for my own needs from the hoar-frost. I have often had to work for hours to replenish my reservoir with sufficient hoar-frost. And I had quite enough fuel to melt the ice! Is it any wonder that only a few plants, a few living creatures can eke out a living here?[1]

Schiaparelli and Lowell ought to be able to have a look about here. Their tales about the *canals* here and hence the highly cultured inhabitants of this planet tempted me to pay this visit! I wish they were able to come here too, and see how even the very first drop of water is lacking. If only they could come and see with their own eyes the variation between the bare heights and the lowlands covered with

[1] Does the writer here refer to animals? Certainly not to reasonable beings. From the fragments of his diary we get the impression that he was constantly alone there. But are there perhaps some small animals, insect-like creatures, that live on the plants? We do not know! The parts of the diary that we have make no mention of the fact.

plants. They would never find their canals. There are no thick caps of snow and ice, the water of which when melted flows in tremendously wide canals, sometimes double ones, to the middle of the planet. There are not even ditches, or tracks. Yet there is some truth in their theories. It is the alternate evaporation of the two polar caps that makes the air moist enough for some months of the year to make it possible for plants to grow in the lower latitudes. Their canals are through the air! And where, in places, in a long, narrow valley, plants spring up, a dark strip is really formed!

But I recently saw myself how pardonable their error, their optical delusion, was. I was looking up at the Earth, at Europe, through my telescope. I saw one channel there, the English Channel. So that was all right. But as I gazed I found that it looked as though there were many more. All dark, scarcely visible spots in Europe seemed to be connected by thin black lines. Europe showed a network of canals that must each be many miles wide!

January 15.[1] For the sake of those who, in spite of my gloomy experience on the whole, wish to make this voyage too, I should like to make the following observations on the equipment required for the expedition. A large quantity of provisions, as for an Arctic or Antarctic expedition for many years, is a first requirement. It is quite easy to keep the provisions here owing to the permanently low temperature in the ground. If economically used, sufficient water can be obtained by melting hoar-frost.

As for clothes—summer clothes are needed, if the tropics are to be visited, for the few hot hours in the afternoons, when the sun may really be very hot. For the rest, the very thickest winter clothes are an imperative necessity. And also cooking apparatus, and so on and so forth, just as for a Polar expedition. Fuel is found on Mars in sufficient

[1] This is the last fragment left. It is near the end of the diary. Shortly after this he must have returned to Earth.

quantities. The dead, dried plants burn well and give a fair amount of heat. There is enough oxygen to allow of combustion.

For breathing purposes a number of first-rate apparatus are needed. It is quite impossible, even during the fine perihelion days in the tropics, to breathe freely in the open air. I tried to do so several times, but was invariably within suffocation in a very short time. A good diving-suit, with an apparatus to condense the air to the right degree, is a necessity. I constructed an electric apparatus that has given me great satisfaction. It works with the aid of an accumulator battery that I carry along with me (it is quite easy to carry a weight that would be a cumbersome load on Earth) and that is filled by the engine of my aeroplane. An aeroplane is the only practical means of travelling long distances here. There are excellent, bare landing-grounds almost everywhere. Of course, one's entire stock of petrol and oil must be taken from the Earth.

It is no good having a compass here. On different points on Mars the needle points in different directions. Apparently there is no magnetism on Mars, or else it is too weak for an ordinary compass to respond to it.

As regards the measurement of time, I seriously advise you not to take an ordinary clock from the Earth, or perhaps just one (of course not one with a pendulum) for the sake of comparison. After I had been here for some months I altered my watch (I am a bit of a mechanic). It is most unpractical to measure time by terrestrial clocks and by terrestrial hours. The Martian hours shift every day and give rise to more and more difficulties. So, *à la Mars comme à la Mars*. It is best to divide one's day so that it corresponds with the Martian day. So the watch must be altered so as to make the hour hand travel round once in 12 hours and 19½ minutes (half a mean solar day on Mars). And the minute hand and seconds hand accordingly. One then counts by days, hours, minutes and seconds that are about 3 per cent. longer than those on Earth; there are only advantages but no

drawbacks. One does not even notice the fact, and the great benefit of it is that it tallies with the sun as seen from Mars. One's pulse then makes a few more beats per minute, but that really does not matter. The only thing that I found to be very odd, was that, when I was once watching the Earth's rotation through my telescope, I found that a complete rotation lasted less than 23½ hours. I first attributed this to a miscalculation on my part, until I remembered that I was using too long hours and minutes!

With respect to the calendar, I also advise you to adapt it. If one holds on to terrestrial months it leads to the greatest confusion, especially if one uses Martian days. Hence, after some experience on the subject, I arranged things as follows: the Martian year has 668 days (not counting the leap-years). It has corresponding seasons, but with a considerably longer, be it much less hot, summer half-year (this applies to the Northern hemisphere). On Earth, we inhabitants of the Northern hemisphere associate winter with January, summer with July. Therefore I chose the following calendar, keeping the terrestrial names of the months.

Southern Hemisphere	*Northern Hemisphere*		*Days*		*Days*		*Days*	*Total*
Autumn	Spring	April	64	May	64	June	63	191
Winter	Summer	July	61	Aug.	60	Sept.	60	181
Spring	Autumn	Oct.	50	Nov.	50	Dec.	49	149
Summer	Winter	Jan.	49	Feb.	49	March	49	147
								668

This calendar, though it certainly does not satisfy all technical and scientific requirements, proved to be quite useful in practice. When finding the date by it I always knew at once what season it was and that is the chief point in every calendar.

Most strange are the things that happen when . . .
[The rest of the diary was unfortunately destroyed.]

CHAPTER VIII

THE STARS

The Distances of the Stars

PLUTO is the outermost planet of our solar system. It is about 3,600 million miles away from us. Light, which travels with a speed of 186,000 miles a second, takes 5½ hours to reach us from there. And yet on that planet we are still at home, in our own family circle. But we are now going to leave our home, our solar system, and plunge into the remote depths of Space, where the stars, our sun's sisters, hold sway.

Formerly the term "fixed" stars was generally used. It was thought that these stars were immovably fixed in the vault of heaven, which revolved around us, and that they did not change their places in relation to one another. The "wandering" stars or planets had to be distinguished from the fixed stars, the former having positions in relation to one another and to the fixed stars which were subject to continual change. Now we know that the stars are suns like our sun, that they too obey the law of universal gravitation, so that they must be in motion, and not only that, but that the speed with which they travel relative to one another must be enormous. But they are so far away from us that thousands, nay, tens of thousands of years must elapse before their positions have, to us, undergone any appreciable change.

Of what magnitude, then, are these distances? In discussing the parallax (page 59) we already explained how they can be measured for the nearest stars. What are the results of these measurements? The nearest bright star is α Centauri, a double star, not visible in our regions.[1] So this

[1] There is a faint star, also in Centaurus, which is just a little nearer.

star is our sun's next-door neighbour. Well, its distance from us is some 24 billion (24,000,000,000,000) miles. The nearest but five is Sirius, the brightest star of our winter nights. Sirius is 50 billion miles away from us. It is a remarkable fact that the nearest stars are almost exactly a million times as distant as the nearest planets.

These figures of 24 billion and 50 billion miles tell us very little; they are too large. We cannot visualize such distances. We even run the risk of confusing a billion with a milliard and yet one is a thousand times contained in the other. The Americans use the word "billion" for 1,000,000,000, that is, for what we call a milliard. Formerly the French did the same. But however that may be, a billion tells us nothing. And that is why, for the stars, a more practical measure has been devised: the light-year, i.e. the distance light traverses in one year.[1] For your guidance we shall just express this distance for the last time in miles: it is about 6 billion miles. Now, if you know what a light-year is, you will have no difficulty in grasping the meaning of the expressions "light-century," "cubic light-year" and "cubic light-century."

Light-year and light-century, therefore, are linear and not *time* measures. So it is pure nonsense to write what a German journalist once did, that "Bismarck's memory will live for centuries, nay, light-centuries."

The star α Centauri is 4·27 light-years and Sirius 8·8 light-years away from us. These are our next-door neighbours. Other stars prove to be at a distance of tens of light-years, or even one or more light-centuries.

The Appearance of a New Star

If, by some freak of nature, the light of the stars should be suddenly extinguished, we should see their light for years or centuries to come. It occurs from time to time that we see a so-called new star in the heavens. In reality this is not a

[1] Astronomical scientists now generally use the "parsec," that is the distance at which the parallax is one second of arc. A parsec is about 3·26 light-years.

new star at all, but only a considerable increase in luminosity of an existing star. On account of the time that light takes to travel the intervening distance, we witness a phenomenon that took place tens of years, maybe even centuries, ago. One of the most famous new stars was Nova Persei, in the constellation Perseus. It flared up in the year 1901, and for a time outshone nearly all other stars. There was no denying that an extraordinary event had taken place. But, *ages* ago! When looking at the stars, we behold the past. At this moment other worlds, more than 30 light-years farther from Nova Persei than we, are observing the flaring up of this new star, which to us has long lost its radiance. Thus the light-message of an event is propagated through the Universe!

Travelling with a speed greater than that of Light

For long, people indulged in the thought that if one could travel through space faster than light, equipped with telescopes of unlimited capacity, one would be able to catch up with those light messages. One would then first reach a point where the world's history of a thousand years ago could be seen and studied, then a point affording a peep into the past of 2,000 years ago, etc. Nobody has ever considered this as a workable plan, but theoretically it seemed to be feasible—until the relativity theory made everything collapse like a house of cards. For, according to this theory, the speed of light is the greatest at which matter or energy can travel. *Why* this should be so is not easy to explain, but there is no doubt about it. And this is a great pity, for, according to classic conceptions, we might then not only have seen the past on Earth, but might even have been able to decide whether we or other heavenly bodies moved in space! For suppose that, being on star A, I look at star B. If the latter body moves away from me with a speed twice that of light in a straight line, I see an event that has taken place on B one year after the movement started, at the end of two years. For in that year star B, which was first close

to A, has travelled on with a speed twice that of light, so has reached a point that is *two light-years* away from me. The light message of an event then taking place will reach me after two years. An event occurring still one year later will be seen by me after four years, one occurring one month after the second event, after four years and two months, and so on. In short, the whole *future* history of star B I see unrolled before me at half-speed. *This is the slow-motion film.* It is the diver who is seen to glide quietly and slowly from the diving-board down into the water. If, on the contrary, body A, carrying me, moves away from body B with the same speed (twice that of light) in a straight line, I see after one year what happened on B two years ago, that is one year before my departure. Travelling on for another two years I see what happened on B four years ago, that is, two years before my departure; in other words, I see the history of B reversed, but at normal speed. This film we also know: it is the reversed film, the diver who, legs upwards, "dives up" from the water to the diving-board. Well, the first picture, as you have seen, is quite different from the second. If the first is seen I am certain that star B moves, if the second picture unrolls itself, I know that I myself (with body A) move in the opposite direction. So if a velocity greater than that of light were possible, it would by no means be indifferent which of the two bodies moved. But alas—the new theories on relativity have quashed all these conjectures and speculations.

Enough of this. Let us return to the bewildering distances in space. And we must repeat what we said before, but now with even greater emphasis: how vast this emptiness is!

The Emptiness of Space

First of all, let it be remembered that the distances between the stars are, on an average, some tens of millions of times their diameters, so that in a straight line between two stars there are, to each unit of matter, tens of millions of units of

emptiness. In our minds we may break up all stars, and all matter the Universe contains, into atoms, and distribute these evenly over the whole Universe. There will then at best be only *a few* atoms available for each cubic metre of space. In the highest vacuum we can attain by means of an air pump there are still billions of atoms present in the same space.[1] So matter is the exception in the Universe: emptiness is the rule. Nothingness reigns almost everywhere. An entirely void Universe would not materially differ from the existing one. But is a world space without any heavenly body possible or even conceivable? Does not the very idea of space presuppose at least one body?

These philosophical problems we shall, at least for the moment, leave alone. It is an established fact that the existing Universe, by terrestrial standards, is practically void. And in this Universe of ours we measure distances by light-years, and light-centuries, and time (as we shall see presently) by milliards and billions of years.

For a moment, we feel our heads swim. What inconceivable distances in space and time! Can this be true? Can such distances exist at all? We do not know, and a certain doubt assails us.

What is Long, what is Short?

To conquer this doubt one cannot do better than try to realize exactly what is meant when a distance is called *great.* What is great, what is small? Of course, we all know, even from childhood, that great and small are relative notions.

Take, for instance, the village green where we used to play as children. How large it seemed to us, and how small we thought it when revisiting it afterwards, as grown-up townsfolk! What heights the Downs had in our juvenile eyes, and how small they appeared to us after we had visited the Alps. And how insignificant the Alps—and even the Hima-

[1] In the world-famous low-temperature laboratory in the University of Leyden (Holland) they have, by a different method, succeeded in creating a vacuum exceeding even the most rarefied parts of the Universe.

layas—seemed when we got to know the dimensions of the Earth. Again, how small this globe was, compared to the sun; the sun, to the vastness of the solar system; the solar system, to the Universe. And conversely, what heights were the Downs compared to the tiny mole-hill, how infinitely large that mole-hill was as against a grain of sand. This grain of sand, in its turn, became a veritable rock by the side of the infinitesimal smallness of the atom! The atom, which has a diameter of about one fifty-millionth of a centimetre (1/50,000,000 cm.)!

Large and small are relative notions, we all know they are, yet too often we seem to lose sight of this truth. For, when judging whether something is large or small, we are too apt to measure by what happens to be our own height. Man is the gauge by which all things are measured; that is what the ancient Greeks said long ago. An elephant is a big animal, a mouse a small one. The distances in space are great, those in an atom small. The latter sentence does not contain greater wisdom than the former. It is no mere chance that the unit of our system of measures is of the same order of magnitude as Man.

Curiously enough, the dimensions of Man are about half-way between the atom and the average star. The human body contains about 10^{27} (ten multiplied 27 times by itself, therefore a thousand quadrillion) atoms; 10^{28} (ten thousand quadrillion) men contain enough matter to build up an average star. Hence, Man is slightly nearer to the atom than to the star. (Thus Eddington.)

So once more, what is long, what is short; what is large, what is small; what is far, what is near? If we want to measure a certain distance, we must have a gauge. We use the rather arbitrary yard, or a multiple or a fraction of it. Hence we express a certain length in another, more or less arbitrary, length. But then the question may be put: what *is* the length of a yard? Present-day scientists will probably answer this question by assuring you that a yard contains so and so many millions, etc., wave-lengths of light of a given

colour. And if you ask them how long such a wave-length is, they will give you an accurate number in fractions of millimetres. And we are still no further than before. We express one length in another, and that again in another. So we do nothing but compare lengths, giving *relative* measures. And we cannot get to any absolute length.

It is the same with time. We reckon by hours, minutes and seconds. For this we consult our clocks and watches. But we are all of us fully aware that our clocks do not show the exact minutes and seconds. The astronomical observatories give us the exact time every day; they check the clock by the exact duration of the Earth's axial rotation. So, perhaps unconsciously, we measure almost any length of time by the duration of the Earth's rotation, or by fractions or multiples of it. But is the axial rotation of the Earth an absolute measure of time? It is an excellent, *practically* invariable measure. But we have already found that the axial rotation is probably slightly *retarded*, hence our measure of time becomes longer, be it ever so slightly, by only a minute fraction of a second per century! How can astronomers find out whether this measure of time changes? Obviously, by measuring it with the aid of another time unit, e.g. the year. But is that unchangeable? Unchangeable, in relation to what? And thus we are always faced with the same difficulty. We only find proportions, *relative* values, no absolute measures.

Henri Poincaré's World

All this may be clearly illustrated by an example, which first suggested itself to the great French scientist and mathematician, Henri Poincaré.

Suppose—says Poincaré—that in a certain night, while you are quietly sleeping, *all* dimensions of all men and living beings and of all objects on Earth and in the Universe, in short, all dimensions without any exception whatsoever, should by some miracle be enlarged or reduced ten or a thousandfold, or even a million times. What would your impression be on awaking and getting up? What would the

world be like, and your bed, which would be 1,200 miles *(when enlarged a million times)* or 2 microns (when reduced *a million times) long? Do you think you would feel that you* were in a strange, entirely changed world?

A moment's thinking will tell you that this would not be so. *It would make no difference whatever to you.* Every-*thing* would be as it was. For if you were then to measure *the length of your room* of 2,300 miles with *your rule, which the day before was one yard long,* you would find *that it* was contained exactly four times in the length of your room. And this is quite natural, because your rule, too, is a million times as long as the day before.

This may seem to you a harmless, or, if you like, even childish, speculation; but on second thoughts you will find that there is a deeper sense in it. It shows you incontestably that it is only *relative proportions* of length that matter. If I were to assure you that a miracle had happened in the past night by which the dimensions of the Universe had shrunk a trillion times, so that Sirius was now at a distance which up to yesterday we called a finger's length, you would not be able to prove the contrary. And if I were then to assure you that I made a mistake and that the exact reverse had happened, notably, that all dimensions had been magnified a trillion times, so that to-day my finger reached to the point where Sirius was yesterday, you would have to admit again that you cannot possibly prove me wrong. Neither one nor the other miracle would change our world in the least. The macrocosm is in no way different from the microcosm. Lilliput and Brobdingnag (the example is Eddington's) do not only resemble one another, they are completely identical—until a Gulliver arrives on the scene to provide a comparative gauge.

What applies to space is equally true for time; we find the well-known analogy here. It was again Poincaré who directed the world's attention to it. If, in some other night, while you are quietly sleeping, all movements, none excepted, were to be retarded or accelerated ten, a hundred or a million

times, if all physical and chemical actions on Earth and in the Universe were to be accelerated or retarded a million times, including the physiological ones, the beating of your heart, your breathing and the velocity of your thoughts—what difference would that make to you on getting up in the morning? What would the world be like, in which it would take you a century to pull on your boots (movements retarded a hundred million times), or in which the rest of your life were to rush by in some fifteen seconds (movements accelerated a hundred million times)? Here, too, the answer is clear: no difference whatever! I may regard billions of years as seconds, seconds as billions of years, provided I shorten or extend all happenings proportionally. *There is no absolute Measure of Length, there is no absolute Measure of Time. Both are equally meaningless.*

We trust that the reader will now see that it is more than a children's game and that we have gained an important insight into these matters of space and time, which have only been common property to the scientific world for some tens of years. It has its practical use too. If we have learned to detach our minds from the chance dimensions of our bodies and from the, likewise, chance duration of our lives, we shall be able to rise mentally above time and dimension. We shall then, at a certain moment, be able to exclaim with full conviction: "Only a light-century? But surely this is not possible, that would be ridiculously near!" Or: "Three milliards of years? In such a short space of time this development cannot have taken place!" Then there will be a time when we shall be able to see the whole Milky Way before us within the dimensions of one cubic yard. Or conversely: traverse the wellnigh "infinite" distances between electron and nucleus of a hydrogen atom. Or, again, we may see the birth of our solar system happen before our very eyes in a few minutes' time. Or, conversely again: we may see the molecules of a gas sail majestically past and about us. And if only we detach ourselves from our surroundings, all this is perfectly true in every respect!

The Distances of the Stars (continued)

Let us return to the distances of the stars, expressed in the usual measures of light-years and light-centuries. We know that by means of the parallax (*see* page 61) we are able to find the distance of a given star. That is to say, if it is near enough to us. For, although the methods of astronomy are being continually perfected, so that at present hundredths of seconds of arc can be measured with great accuracy and thousandths with tolerable approximation, the stars whose distances are known as a result of parallax determinations are only a few thousands in number.[1] The other stars are so far away from us that even a displacement of ourselves, as observers, over the whole diameter of the Earth's orbit, does not change their places in the heavens appreciably.

How, then, are we to make any progress? To form an idea of the structure of the Universe, we shall at least have to know the distances between the stars! And we know them of a mere handful of stars only!

Kapteyn's Work

Quite so: such was the condition of science half a century ago.

But the astronomers were not content with this state of affairs, and under the guidance of some prominent men, among whom the Dutchman, Kapteyn, deserves special mention, ways and means were devised to arrive at more satisfactory results. They reasoned as follows: suppose that all stars at the same distance were equally bright, in other words, that their luminosity (their candle power) was the same, then they would gradually weaken as their distance from us increased. For the brightness of a source of light decreases as the square of its distance. If we make a print of the negative of a photo at a distance of two feet from an electric lamp, we must expose it four times as long as at a

[1] In 1910 the number was only 365, in 1924 this number had increased to 1,681, and in 1934 to 3,706.

distance of one foot. And at three times that distance nine times as long, and so on. So, given the same candle-power, we might conclude that a star which, to our eye, is a hundred times fainter than another, is ten times as far away from us. And, since the parallactic method has given us the exact distances of some thousands of stars, we should have found an easy way out of the difficulty.

But, unfortunately, the supposition that all stars at the same distance are equally luminous does not hold good. They are of different luminosity. Yet, when dealing with a very large number of stars, the supposition must be correct as a statistical average. The stars which from the Earth we see as faint are, *on an average*, certainly farther away than those seen as bright. Incidentally, this indeed proves to hold good for the few thousands of distances we know accurately. And it is perfectly natural, too: the luminosity of a star is independent of its distance.

There is a second point to be considered. As we shall presently see, the stars also appear to have proper motions. It is far from easy to determine this motion. This, too, we shall soon experience. But, all the same, it *is* possible to do it. The argument here is pretty much the same as in the case of luminosity. If all stars had the same velocity, hence, the same absolute annual proper motion, we should only have to measure their apparent movement in the sky to determine their distance. The larger this apparent movement, the closer the star; the smaller this movement, the farther away the star. We shall, for the moment, leave the direction of this movement out of account; a star coming towards us, or receding from us, in a direction exactly in our line of sight has no apparent motion at all; if it moves in a plane at right angles to that direction, the apparent movement is greatest. This makes the whole matter still more complicated; but for the moment we may disregard it, because, when considering a very large number of stars, it again comes to the same thing *on an average*. And, as a general average, the conclusion might be drawn that the smaller the apparent

movement, the farther away the star. However, the supposition that all stars have the same velocity in space is not correct either. Yet here, too, the stars' apparent proper motions may afford a valuable mean, and from the couple of thousands of distances which are accurately known it has, in fact, transpired that, on the whole, the nearest stars have the greatest apparent proper motions.

And thus Kapteyn was able to draw up a scale, which made it possible to determine the distance of a star with a fair degree of accuracy from its brightness, on the one hand, and from its apparent proper motion on the other. It follows from the above that a considerable mistake may be made for one particular star, but *on an average* the results must be fairly reliable. This method enables us to form a fairly accurate idea of the distribution of the stars and of the structure of the starry universe.

Fortunately astronomers did not stop at this rather rough method of estimation. New methods have been devised to determine the exact distances of the stars.

The Spectrum comes to our Aid

The astronomers Kohlschütter and Adams, in 1918, discovered that from the spectra (*see* page 169) of certain stars conclusions may be drawn as to their luminosity. For this the brightness of certain lines in their spectra in relation to one another should be compared. So, if one considers the spectrum of a star whose distance is unknown, and if the spectral lines in question are clearly discernible, and their relative strength accurately determinable, the candle-power of that star is known. The distance of the star then follows directly from the brightness observed. Now, this method can only be applied to stars of which a clear spectrum can be obtained. But this is possible of a great many stars. Thus, the number of stars whose distance is accurately known to us is continually increasing, while the available data allow us better to see how far Kapteyn's approximate method of average values yields satisfactory results.

The Cepheids

Among the number of methods that have been discovered of late years there is one which, so far, has given quite exceptional results. I am here referring to the famous method of the *Cepheid variables*, which has enabled astronomers *to fix the distances of these stars and of many groups of stars in space with a fair degree of accuracy.*

Variable Stars

What are *Cepheid variables?* They are—as their name tells you—variable stars. There are a great number of stars that do not shine with steady light, but whose brightness varies. There are at least five classes of variables. One class owes these light-fluctuations to periodic star eclipses: a dark globe, or at least a much less luminous one, turns round the star in a certain period; obviously, this movement must occasion light-fluctuations that return at regular intervals (e.g. the well-known star Algol). In other cases the two stars are equally bright or nearly so, and, seen from the Earth, they are so close together as to be seen as one star. If, now, one of them circles round the other exactly in the plane containing the Earth, it will cover the other at set intervals and their light must then be less strong. Still others exist in which the fluctuations appear to be more or less irregular, the cause of which is at present unknown. A fourth class is formed by the "new" stars. These are faint stars which suddenly flare up in a phenomenal blaze of light, to fall back to their old insignificance after a few months or years. The cause of these violent outbursts is still a matter for debate, although astronomers, in their efforts to find an explanation for this phenomenon, are making headway.

Finally, then, there are the Cepheid variables, which owe their name to star δ of the constellation Cepheus. For a long time this star had been observed to fluctuate in brightness with great regularity, each period taking exactly 5 days, 8 hours and 47 minutes for its completion, year after year. Not only this, but the periods of fluctuation were distinctive

in another way too: first a rapid increase of light in about 1½ days, followed by a slow gradual decline in about 3½ days. Such changes cannot be due to an eclipse. The nature of the star itself must here be responsible. Some insight at least has been gained into the causes of these light-fluctuations. Cepheid variables are freely scattered in space, and their light, in all cases, fluctuates in the same way; only the periods differ. Now the American astronomer, Miss Leavitt, made a discovery of vast importance to astronomical science. To understand this properly, it should first be mentioned that even among the stars whose distances are accurately known there proved to be some Cepheids. Well, what Miss Leavitt discovered was that *Cepheids with the same period of light-fluctuation invariably appeared to have the same luminosity. There was sufficient reliable material available to determine the luminosity for each period of light-fluctuation.*

So, if somewhere in the world's space we observe, at an unknown distance, a Cepheid with a certain light period, we know at once that it is a bulb of 100 candle-power. Of another one with a different period we can say: that one emits a light of 150 candle-power. Still another period means 200 candle-power, etc. And this settles the question at once. For if an electric bulb of known candle-power burns at an unknown distance from me, I can always calculate its distance. From its candle-power on the one hand, and its apparent brightness on the other, its distance follows directly. The only condition I must make is that there may be no mist, vapour or dust to intercept the light of the lamp. The same condition applies to the Universe. The Cepheid method is only reliable if the world's space is sufficiently free from interstellar matter. But fortunately this condition proves, in the main, to be fulfilled in the Universe. There are only a few regions of the heavens where dark interstellar clouds are to be seen. They are the exception. For the rest, the Universe may be considered as almost entirely transparent, although it is an established fact that a small part of the light is absorbed by the infinitesimal particles of

interstellar matter, and that this absorption seems to be most pronounced in the area of the Milky Way.

Thus we can measure the distances of all Cepheid variables with great accuracy. And, as we have said, there are quite a lot of these stars.

Double Stars

We are further helped by a number of fortunate circumstances which we are now going to deal with. There are, in the heavens, a great number of what are called double stars, that is, stars which, to the naked eye, appear single (or may, rarely, just be seen close to one another), but are found when examined in a telescope to consist of two (sometimes more) separate stars. In some cases this is mere chance (optical doubles). We then see the two stars nearly on the same line of sight, although one is perhaps a thousand times as distant as the other. But in by far the majority of cases two such stars really belong together; they are, relatively speaking, very close to one another and they revolve in periods ranging from less than one day to hundreds of years round their common centre of gravity. Such stars may be considered as practically equidistant from the Earth. If one of them is a Cepheid we can determine its distance, which at the same time fixes the other's distance.

Star Clusters

And there are other things too. There are also star clusters, to which we will revert later. They number thousands or even tens of thousands of stars. These star clusters are so far away from us that the differences in distance of the several members may be disregarded, so that for practical purposes they may be looked upon as equidistant from the Earth. In these clusters there sometimes occur Cepheids (or stars which for our present purpose may be regarded as on a line with Cepheids) which fix the distance of the whole cluster.

Nebulæ

Finally, we must make mention of the nebulæ, the most distant objects in the Universe. Their distances will be discussed in a subsequent chapter. You will then see that in regard to them, too, we are no longer completely groping in the dark. We are able to measure distances of more than a hundred million light-years!

It is not more than a century ago that for the first time the distance of a star (61 Cygni) was measured by Bessel (*see* page 62). Half a century later the distances of perhaps a hundred stars were known. The very greatest distances astronomers had succeeded in measuring were light-centuries. We have now measured millions of light-centuries. What to Kapteyn was still a fervent wish, viz. to find the distances of all stars and of all other heavenly bodies, has now been realized in a general way. So rapid is the march of Science!

The Magnitudes of the Stars

In speaking about the magnitudes of the stars, one should be careful to be quite clear as to what is denoted. For different things may be meant. It would be preferable if the word "magnitude" were exclusively used for what in everyday life is denoted by "size." For instance, we have said that the Earth has a diameter which is almost four times that of the moon, so that the size of the Earth proves to be nearly fifty times that of the moon. In a similar way the sun has a size of more than a million times that of the Earth, because its diameter is more than a hundred times as long as ours. And thus we might also try to find—an effort which has actually been crowned with success—the number of times the diameter of a given star is larger or smaller than that of the sun, and deduce from this proportion the size of the star compared to the sun.

But in speaking of the magnitude of a star we, for the present, do not mean size but something else. We speak of stars of the 1st, 2nd, 3rd, etc., to the 21st magnitude,

thereby indicating the star's apparent magnitude, its *brightness* as seen from the Earth. The stars of the first to the sixth magnitude are visible to the naked eye. We took this classification from the Ancients. They divided all stars visible to the naked eye into six classes of brightness or magnitude. Other stars they did not know. Herschel discovered that first-magnitude stars make (roughly) 2½ times as much light impression on our eye as those of the second magnitude; those of the second magnitude 2½ times as much as those of the third magnitude; and so on. From this it follows that a first-magnitude star, seen from the Earth, makes about a hundred times as much light impression as one of the sixth magnitude. Of course, the light impression of all stars of one and the same class of magnitude is not exactly the same. At present the magnitude is even indicated to the second decimal. Moreover, the number of classes has now been extended, since the stars which can only be seen in a telescope have been classified. The faintest stars which can yet be photographed through the most powerful telescope are of the 21st magnitude. The classification has been continued in the same way: every new class contains stars which are, on an average, 2½ times as faint as those of the next brighter class. Hence, a star of the 12th magnitude makes a light impression of 2½ to the 11th power, or about 25,120 times as small as one of the first magnitude. To the other side, too, the scale had to be extended: an O class has been added, and even a minus one class, in which of the fixed stars only Sirius figures with a magnitude of −1·9 (Venus, when at its brightest, can attain a magnitude of −4·3). The light we receive from the brightest star is to that of the faintest, which is still visible (or rather, can be photographed) in the Mount Wilson telescope, as 1,500 *million to one!* Remember, this apparent magnitude or brightness of a star should be carefully distinguished from its *intrinsic* luminosity (candle-power). The luminosity of a star is the light it actually emits, independent of the distance at which we are from it. According to their luminosity the stars are grouped into classes of

absolute magnitude. We saw how the absolute magnitude of a star can sometimes be deduced from its spectrum and how in the case of the Cepheids it is always known to us. We then turned this knowledge to account to find their distances via their apparent magnitudes. Conversely, with the stars whose distances we have come to know by some other means, we can now determine the luminosity from those distances and their apparent magnitude.

Thus it appears that the luminosity of Sirius is twenty-six times that of the sun. The calculation to be made is quite simple, and that is why we shall illustrate our theory by means of this example. Sirius is more than eight light-years away from us, that is, more than half a million times as distant as the sun. The light impression decreases with the square of the distance. So, if our sun were ten times as distant, we should receive one-hundredth part of the light we do now; if it were as far away as Sirius we should receive (more than half a million) times (more than half a million) times less light, that is, less than $\frac{1}{200,000,000,000}$ of its present light. This quantity can be accurately calculated. Well, Sirius emits twenty-six times that quantity.

And now, would you like to hear the extremes of absolute magnitude of stars? The weakest star known is Wolf 359, whose candle-power is $\frac{1}{60,000}$ of our sun; the brightest star is one of fluctuating strength, S. Doradus, varying from 300,000 to 500,000 times the candle-power of our sun. As Jeans rightly says: If we compare the sun to a candle, Doradus is a lighthouse and Wolf 359 a glow-worm.

But do not let these extremes (S. Doradus has 25 milliard times the candle-power of Wolf 359) misguide you. They are and remain, to all intents and purposes, extremes. On an average the relative candle-power of the stars differs much less. And our sun is not far removed from the average.

The Dimensions of the Stars

Let us return to what in everyday life we designate the size of the stars. With the planets the problem was in nearly

all cases easy to solve when we had determined the distance. For then, the only thing we had to do was to measure the apparent diameter, which enabled us at once to calculate the actual size from the distance. But planets seen through a telescope present a measurable disk, except for Pluto and most of the planetoids. And these exceptions at once bring us face to face with the difficulty; we know the distance, we see the heavenly body in question, and yet we have a good deal of trouble in finding its actual size on the strength of indirect data.

It is the same with the stars. We now know their distances, we also know their luminosities. But their real dimensions? Not a single star, even when seen through the most powerful telescope, presents a measurable disk, since the stars are so far away from us that they are never visible but as points of light, so that we cannot measure their diameters. But man is a cunning animal! In spite of everything, astronomers have actually contrived to measure the diameters of four of the very biggest stars, without being able to see these diameters. The means were ingenious indeed, but not fictitious! They used the interferometer, and in this instrument the unseen diameter is actually measured. Thus we have come to know the dimensions of four stars, viz.:

Betelgeuse............	radius = 250 times that of the sun
Antares................	radius = 460 times that of the sun
Aldebaran............	radius = 50 times that of the sun
Arcturus...............	radius = 24 times that of the sun

These are real *giants*. The best way of forming an idea of their sizes is to consider that the whole of the Earth's orbit could easily be fitted inside either Betelgeuse or Antares! The radius of the Earth's orbit is only 120 times that of the sun.

So, by means of the interferometer, we have found the sizes of four stars. However, in the case of the other stars[1] even this instrument has so far proved to be powerless. Hence, in order to find the dimensions of the stars, recourse

[1] As better and larger interferometers have been constructed this number will no doubt soon increase, if it is not greater at the present moment.

must be had to different means. And if you are not already convinced of it, let me assure you that astronomers are not easily discouraged!

It is not difficult to map out the course now to be taken; probably the reader himself would be able to find it independently. We know the total quantity of light radiated by a star; if, now, we could also determine the amount of light emitted per unit of area, e.g. per square mile, a simple division would give us the number of square miles of the star's area and hence the other dimensions as well. Now, it actually proves to be possible to find the amount of light radiated by a star per unit of area! We shall here give an explanation in a simplified form. In reality it is a little more complicated, but it is the underlying principle that matters.

The stars clearly show different colours. Even with the unaided eye we see some stars yellower than others, some as having a ruddy hue. In a telescope you can distinguish dull-red, orange-red, yellowish, white and bluish-white stars. This difference in colour can also be determined in another way; for instance, by investigating what effect (strong or weak) the light of a star has on a photographic plate.

In any case, the colour of the light of any star can be accurately determined. Now, what causes this difference in colour? Investigation has shown that it is due to difference in temperature of the star's surface. Dull-red stars are coldest; their surface-temperatures vary, round about 1,400° Centigrade. Orange-red stars have a temperature twice as high or more. Next follow stars like our sun, with a yellowish colour and a surface temperature of about 5,500°. And thus we go on until we arrive at the white and bluish-white stars, which exhibit a surface-temperature of no less than 40,000° Centigrade. All these temperatures can be determined with a fair degree of accuracy for the different stars. Further, it is possible to calculate the amount of radiated energy leaving a given area at a given temperature. These calculations can be partly checked in our laboratories by experiments; but temperatures of 40,000° are far beyond

our reach. Yet we can accurately calculate (checking our calculations to a considerable extent by practical tests) what amount of energy is radiated by a surface of, say, one square yard at a temperature of 1,400° and how this radiation increases as the temperature increases to 40,000°; in this way we obtain a scale of temperature and radiation. The difference proves to be immense. The radiation of the coldest star (1,400°) is, per like unit of area, only $\frac{1}{350,000}$ part of that of the hottest star (40,000°). A star of the hottest grade radiates as much energy as one having 350,000 times its surface area but belonging to the coldest group.

The whole reasoning and computation is now clear. We determine the colour of a star. More precisely, the intensities in the red and blue ends of the spectrum are measured and the surface temperature deduced. We can now read from our scale the amount of energy radiated per square mile by a surface of that temperature. We know what part of the radiation is light and what part is heat, etc. If we know the star's luminosity we know the total amount of light radiated, and this divided by the amount of light per square mile gives the surface area, from which all other dimensions can be deduced.

If, now, we compare the dimensions of the four above-mentioned stars thus determined with those found by means of the interferometer, a substantial agreement is shown. This leads us to believe that the results we have attained by this method may be considered as reliable.

The dimensions of the stars prove to vary widely. The smallest star so far found is that named van Maanen's star, after its discoverer, van Maanen, a Dutch astronomer. This star is not larger than our Earth! On the other hand, there are other extremes. We have already made the acquaintance of Antares and Betelgeuse: balls of gaseous matter the size of a considerable part of our solar system! However, van Maanen's star and Antares and Betelgeuse are extremes, exceptions. The vast majority of the stars have dimensions in the vicinity of the average and

our sun, too, is not far removed from the average in this respect.

So, we have seen how the dimensions of the stars can be found. Now a word about their masses.

The Mass of the Stars

When discussing the various members of the solar system we already saw that the *capacity* (the volume) of a body should be carefully distinguished from its *mass*. Thus the moon proved to have a volume of about $\frac{1}{50}$ part of the Earth, whereas its mass was less than $\frac{1}{80}$ part of that of the Earth. This need not surprise us; in everyday life we can see many examples of the same kind. The weight of a cube of wood, for instance, is perhaps $\frac{1}{40}$ part of the weight of a cube of gold of the same size. The capacities, i.e. the volumes, of the cubes are the same, but their weights are different. That is because the specific gravity of gold is much higher than that of wood.

Now, how can we find the weight of a star, or rather its *mass?* In the case of the sun, the planets and the moons this could be done because from their movements we were able to deduce their mutual attraction. The general law of gravitation applies everywhere in the Universe, hence also to stars. In a number of cases the determination of a star's mass is, in principle, effected in quite the same way. We must calculate the gravitational force two stars exert upon one another. This is possible with the double stars which we already discussed. There are many double stars. Almost 50,000 of them are known at present. It is no easy task to ascertain the exact orbits of the components (the separate members) of the double stars. The investigator is faced with several difficulties both of a practical and a theoretical nature. But yet, the common mass of the two components of a fairly large number of double stars has now been calculated from their orbits, while in a number of cases also the mass of each of the components can be deduced.

Eddington's Mass-luminosity Law

The total harvest of stars whose masses are thus known with complete or with reasonable accuracy is not large. Their number is not larger than fifty. Is there no other way to find the masses of the other stars, or at least of the vast majority of them, within reasonable approximation? To be sure there is, Eddington has shown us the way. On the strength of theories on the state of the atoms inside the stars Eddington became convinced that with the vast majority of stars there must be a direct correlation between mass and luminosity. This is the famous mass-luminosity law, by which the mass can be deduced from the luminosity and, conversely, the luminosity from the mass. Eddington tested his theory by the above-mentioned fifty stars. There appeared to be extremely gratifying agreement between theory and practice. All these stars proved to lie on, or very close to, the curve which Eddington had plotted on the strength of his theory.

This curve affords us the means of finding the masses of the vast majority of stars with reasonable accuracy. The luminosity of a number of stars is directly known to us (for instance, that of the Cepheids); for others it can be inferred from their distances and their apparent magnitudes. Now, Eddington's law enables us at once to find their masses. Properly speaking, we should not take their luminosities but their heat-intensities. The latter quality, however, is intimately related to the former. Well, how do we determine the mass of a star by Eddington's law? For this let us have a look at Fig. 29. The vertical line on the left is a scale indicating luminosity (or rather, heat-intensity); the number near the bottom (12) indicates a low, that near the top (4) a very high, intensity. The horizontal line is a scale on which the masses are plotted; to the left are the very small masses, to the right the very large ones; 0.0 in this scale is the sun's mass; 1·0 corresponds to a mass ten times that of the sun. The place of the sun on the curved line (curve)

is found by travelling right up from 0·0 until the curve is reached; to find the sun's luminosity proceed horizontally to the left from the point on the curve just found. You will then arrive somewhere near 5 on the light-scale. How do we determine the mass of a star having a luminosity of 2? We start from point 2 on the vertical light-scale, proceeding to the right until we reach the curve, and then travel vertically downwards. We then arrive at about 0.3. So our star figures with a label "0.3" in the scale of masses. Since this is a logarithm (we shall not here enter into the

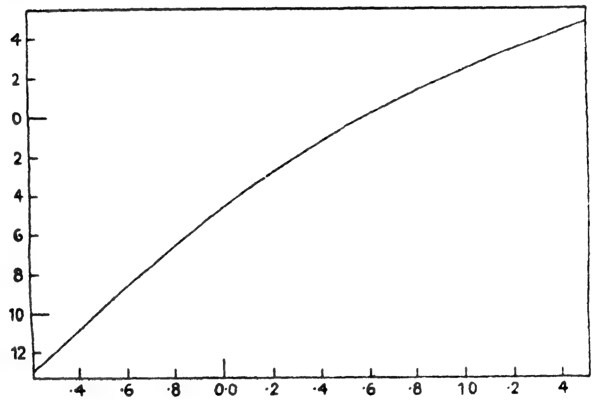


FIG. 29.

mysteries of logarithms, although they are not very deep) it means that the mass of the star in question is about 2½ times that of the sun. Thus we are nearly always able, whenever we know the luminosity of a star and hence its place in the vertical scale, to find its mass in a simple way. The masses of a great number of stars can in this way be found with a reasonable degree of accuracy.

The results obtained show that the masses of the stars vary much less than their sizes. There is not a single star with a mass smaller than 10 per cent. of that of the sun. There are only few stars exceeding the sun's mass tenfold. So also in point of mass our sun is, approximately, an average. It also follows from all this that, generally speak-

ing, the biggest stars have the smallest densities, the smallest stars the greatest densities.

In this connection we must mention another case that ranks among the finest accomplishments recorded in the history of modern astronomy. To my mind it even greatly surpasses the most wonderful achievements in connection with the solar system, such as the discovery of Neptune. What I refer to is the case of the Companion of Sirius.

The Companion of Sirius

Sirius is the brightest star in the heavens and at the same time the nearest but five. Needless to say that it has been watched by astronomers thousands of times; it was at first sometimes used (in connection with the apparent daily rotation of the celestial globe) to determine the exact duration of the Earth's axial rotation. It soon turned out, however, that it was subject to irregularities; it was not always in its proper place. And then, in 1844, Bessel discovered that Sirius described an extremely small elliptic orbit in the sky. Sirius does this in a period of 47 years. This could only be explained by assuming that Sirius was a double star, hence that it turned round another star, or rather, round a common centre of gravity with that star. But the other star was—and remained—invisible. First peculiarity: an invisible star is discovered. Clark, in 1862, actually observed the companion. Now, the distance to Sirius is very accurately known (it is a near-by star) and, of course, its companion is, for all practical purposes, at the same distance from us as Sirius. From the orbits of the two stars, which in this case were precisely known, the mass of Sirius's companion could be deduced indubitably. It proved to be no less than $\frac{4}{5}$ of that of our sun. So, in point of mass, the companion of Sirius was quite a respectable star! Yet, from the Earth, it is an extremely faint little star; it gives so little light that for years after its discovery it was not observed in the sky. From its apparent magnitude (brightness) and its accurately known

distance followed its luminosity. This proved to be only $\frac{1}{360}$ that of the sun.

So the following data were now available: luminosity, $\frac{1}{360}$ that of the sun; mass, $\frac{4}{5}$ that of the sun. This in itself did not seem so extraordinary;[1] it was simply assumed that the companion did not differ very much in size from our sun, but that its surface was cool so that its radiation per unit of area was extremely slight.

In 1914, however, Sirius's companion was found to be white and hot, and to belong to the stars which radiate a very large amount of light per unit of area. Here was a mystery! For, as we saw above, it was now possible to calculate, from its luminosity and its radiation per unit of area, its dimensions and its volume. This volume proved to be not more than $\frac{1}{50,000}$ part of the sun. So, not more than a fair-sized planet! But its mass was and remained $\frac{4}{5}$ of the sun!

The data employed were of indubitable accuracy. Mass determinations of stars are difficult, but precisely in this case the determination could be made with very great accuracy. The distance to the star was to be considered as one of the best known. Its powerful radiation per unit of area was not open to doubt either. Most incontestable of all was its very small brightness seen from the Earth and hence, also, in connection with its near-by position, its weak luminosity. Thus, by the side of its enormous radiation per unit of area, its very small dimensions were equally established. Volume about $\frac{1}{60,000}$ part of the sun!

It followed, since its mass was $\frac{4}{5}$ that of the sun, that its density must be about 60,000 times that of water. A specific gravity of 60,000! Platinum, practically the heaviest material known on Earth, has a specific gravity of 21. So this star must weigh 60 kilograms per cubic centimetre—the size of dice! The same cube made of platinum weighs

[1] The mass-luminosity law of Eddington was then not yet known. The companion of Sirius belongs to a small class of stars for which this law does *not* hold good.

21 grams. It seemed preposterous! Thus in 1914 and in the years immediately following, the opinion of every sensible person was that somewhere in the calculation a grave error had been made. But the error was not found.

By the year 1924, however, the theories on the structure of the stars and the atoms had so far advanced that it was held possible for the immense heat inside a star to destroy the atomic structure. We have already seen that an atom may in many respects be compared to a solar system in miniature. There is a nucleus round which (thus the system may be represented for comparison) electrons circle in their orbits. In one respect an atom certainly resembles the solar system: there is infinitely more void (space) than matter. Starting from the nucleus there is first a wide expanse (everything in proportion, of course) of emptiness, then comes the orbit of one or more electrons, then nothing for a very long time, then again an orbit, and so on. Indeed, an atom is just as empty as the solar system. Well, if an atom as such is destroyed, its component parts can be stored in quite a small portion of the space which was taken up by the atom. In precisely the same way as the sun and the planets with their moons—if the solar system were smashed up—could be pressed into a space much and much smaller than the solar system.

So now a specific gravity of 60,000 had to be admitted at least as a possibility. People were certainly no longer warranted in calling this preposterous!

But we are not yet at the end of our story. The final effect is yet to come. Einstein arrived on the scene with his theory of relativity. From this theory it *inevitably* follows (how, cannot be told in a few words) that the lines of the spectrum of a heavy celestial body, as compared to the corresponding lines in a spectrum obtained on Earth (*see* page 169) must have shifted towards the red side of the spectrum. For our sun this difference must, according to theory, be very slight only, but experts are now practically agreed that in spite of the great difficulties attending this

investigation, they have succeeded in showing the very slight divergence in the solar spectrum predicted by the theory.

However, if the theory concerning Sirius's companion is correct, the same phenomenon must apply in a much higher degree to that star. For the Einstein effect becomes more pronounced as the mass of the star increases or its radius decreases. If the mass is large and the radius small the effect is strongest. Well, the data obtained had shown that (*relatively speaking*) the mass of Sirius's companion was great and its radius small. The effect, according to Einstein's theory, should be thirty times that on the sun, and should be easy to demonstrate, if only the spectrum of this small star could be properly photographed.

Adams finally succeeded in obtaining a good photograph of the spectrum. There proved to be a pronounced red-shift in the spectral lines. According to theory, this shift should be 20 given units. In reality it was 19 of those units! Taking possible errors of observation into account, this measurement gave a brilliant confirmation of the theory.

The reader will at once grasp the full significance of this wonderful proof. Two of the most hazardous conjectures of modern thinking, conjectures which must make old-fashioned scientists shudder, were here confirmed at one stroke. On the one hand, the modern atomic theory assuming the possibility of smashing up an atom, on the other the revolutionary relativity theory. There is no discovery in modern science that has impressed me more than this one.

Such, then, is the amazing story of the Companion of Sirius. A few other stars of this nature have since been detected. They are called "white dwarfs." White dwarfs are very small stars of very heavy weight and with white-heat radiation. There may well be many more of them. The mass-luminosity law does *not* apply to them.

The Number of Stars

Do you know how many bright stars there are in the

heavens? This question is not difficult to answer. From the Earth there are visible:

Stars of the first magnitude (and brighter still)	14
Stars of the second magnitude . . .	25
Stars of the third magnitude . . .	66
Stars of the fourth magnitude . . .	340
Stars of the fifth magnitude . . .	1,015
Stars of the sixth magnitude . . .	3,260

So in all there are not more than 4,720 stars visible to the naked eye from the Earth. At most, slightly more than one-half of these 4,720 stars are visible on a certain spot at a given moment; the other ones are not visible at that moment. So that brings the number down to about 2,500 that are simultaneously visible to the naked eye. This number then includes all stars of the sixth magnitude, which can only be observed by a person with good eyesight and under favourable conditions. In and near our big towns, in our humid atmosphere, we as a rule do not get further than stars of the fourth magnitude. There are, then, about 225 stars simultaneously visible, and after deducting those that are too low in the sky to be practically visible, about 200 are left. So the answer to our question may be two hundred. And the term "bright" has even then been taken in a rather wide sense, for, properly speaking, the stars of the fourth magnitude cannot be considered as "bright" to the unaided eye. If therefore we also drop these stars of the fourth magnitude, the correct answer to our question must be: about 50, say *fifty*. This number rather comes as a disappointment; by and by we shall hear different figures!

The number of visible stars is already increased about tenfold in a very small telescope; we can then observe thousands and thousands of them. The more powerful your telescope the more stars you will see. And thus through the most powerful telescope now at the disposal of man (the Mount Wilson telescope) not less than about *one and a half milliard* or 1,500 *million* stars can be observed. Mind, no

astronomer or number of astronomers have ever counted all those stars. In the first place not all parts of the heavens are visible to the Mount Wilson telescope. Besides, the faintest stars are not discernible in that telescope either; it is only possible to obtain light impressions of them, which are just visible, on a very sensitive photographic plate that is exposed for hours in the giant telescope. Random tests are then made on a number of such plates. The stars on a plate are counted in the same way as the letters in a book can be counted in a simple way, without it being necessary to count more than some ten lines. If plates of different areas of the sky are thus treated, one arrives at a very reliable estimate, which does not differ more than one or two per cent. from the number of stars which one *would be able* to count in the entire celestial vault by means of this telescope.

One and a half milliard stars. It is quite a lot. This number would already make it possible to present nearly each inhabitant of the Earth with his own star. Yet this number of one and a half milliard is smaller than you might expect to find. For, if one started from the supposition that, as a general rule, the stars are of equal luminosity and that, also as a general rule, they are scattered through space at equal distances from one another, a simple calculation would show you how many stars of the various classes of magnitude should be visible. (*See* Fig. 30 and explanation.)

The number of stars of, say, the tenth magnitude should be about three times that of all stars comprised in the first nine magnitude classes. The number of stars of the sixteenth magnitude should then be three times that of all stars from the first to the fifteenth magnitude inclusive. That is, at least, if our supposition that the stars are evenly scattered through Space is correct. The other conjecture that the stars are of equal luminosity may be taken for granted with such a vast number of them.

Well, it transpires that at first each higher class of magnitude does indeed contain more stars than all preceding

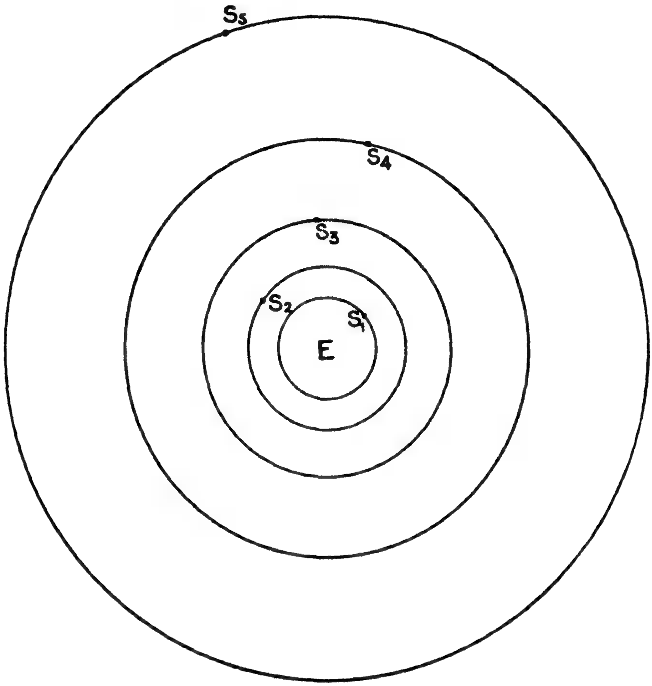


Fig. 30.

THE "THINNING-OUT" OF THE STARS IN SPACE.

E is the Earth. S_1, S_2, S_3, S_4 and S_5, are stars. The figure is a cross section of five spheres, each having its centre in E. The radius of each sphere is as 1 : 1·6 to that of the next larger sphere. So, $ES_5 = 1{\cdot}6 \times ES_4$, $ES_4 = 1{\cdot}6 \times ES_3$, $ES_3 = 1{\cdot}6 \times ES_2$, $ES_2 = 1{\cdot}6 \times ES_1$.

Suppose:

1. That all stars are equally luminous (*this supposition is, as a general rule, correct for a very large number of stars). Then star S_5 will, on Earth, give $(1{\cdot}6)^2$ or about 2·5 times less light than star S_4 (for, did we not see that the light impression decreases with the square of the distance?). Star S_4 will give 2·5 times less light than star S_3, and so on. Hence stars S_1, S_2, S_3, S_4 and S_5 will mutually differ just one class in magnitude. (See text.)*

   Star S_1 is a star which is on the border line of the first and the second magnitude. It then follows that star S_2 is on the border line of the second and third magnitude, star S_3 on the border line of the third and fourth magnitude, and so on.

Now suppose:

2. *That all stars are evenly scattered through space; then each following, larger sphere will contain $(1{\cdot}6)^3$ or about four times as many stars as its predecessor (for the capacities of the spheres increase with the cubes of their radii).*

   In the smallest sphere but one there will then be, round the smallest sphere, about three times the number of stars contained in this smallest sphere. As besides, on the strength of our suppositions, all stars in the smallest sphere are of the first *magnitude (and brighter) and all stars outside this sphere but within the second sphere, of the* second *magnitude, this means that the number of stars of the second magnitude must be about three times that of the first magnitude (and brighter). In the same way we find that there must be about three times as many stars of the third magnitude as there are of the second and first magnitude (and brighter) together. And so on.*

   And now actual observation shows that the relation of three to one is not *reached, and that the "deficiency" increases as the stars grow fainter, hence at increasing distances; in other words,* the stars thin out in space with increasing distances.

stars only form a *very tiny portion* of the sum total of the stars in existence.

The Proper Motions of the Stars

As we saw, the opinion was formerly held that the fixed stars stood motionless in the vault of heaven. The Ancients could not conceive the stars as having motions of their own. When science had provided the world with a better insight into these matters, and the stars were understood to be loose suns floating about in space, people were quick to arrive at the conclusion that those stars, too, could not but continually change their relative positions in the sky. For does not the same law of gravitation apply out there, in the vastness of Space, as a result of which the stars cannot fail to move in relation to one another?

On the other hand, it is a known fact that the "apparent" proper motions in the heavens are extremely small. Even vast speeds must be reduced to quite insignificant displacements at such tremendous distances. History, too, bears out the smallness of these motions as seen from the Earth, for the constellations described by the Ancients are still observed by us unchanged, or at least practically unchanged.

These proper motions are no simple matter. If the star moves in a plane at right-angles to our line of sight we get a full view of that movement, exactly in the direction in which it really takes place. But if that motion happens to be in the same direction as our line of sight, that is if the star comes towards us or recedes from us, we are unable to get a correct idea of the movement, there being no apparent displacement in the vault of heaven. These are extremes; in reality most cases will lie between them. However, a small apparent displacement in the sky may be attended by a very large proper motion of the star, not only because the star is extremely far away from us, but also because this motion is mainly directed towards or away from us.

This is the first complication. To find the proper motion of a star we must know:

1. Its apparent proper motion, that is, its displacement perpendicular to our line of sight;
2. Its radial proper motion, that is, its displacement in our line of sight.

But there is a second complication as well. Our sun is a star like all other stars, and even in every respect an average specimen of the type. It is therefore highly probable, or even certain, that our sun has a proper motion, too, carrying the whole solar system along with it, without this motion having the least effect on what is going on inside the solar system. However, if the sun moves relative to the stars, the latter must seem to move in the opposite direction. This, in its turn, would be quite easy to observe, if all the stars were stationary in relation to one another. But this is far from being the case, for we have just seen that all of them have proper movements. However, we can leave the relation of the sun's proper motion to that of the stars alone for the present; we shall see in a subsequent chapter that of late years fresh light has been shed on this matter. We shall, therefore, now deal with the proper motions of the stars relative to the sun, hence as if the sun were stationary.

The Apparent Proper Motions of the Stars

The apparent proper motions of the stars are generally indicated in seconds of arc per year; this figure is then referred to as the annual proper motion of the star. As we have already stated, this is so small for the majority of stars that it is extremely difficult to measure. Yet it is now known for many thousands of stars. The annual proper motion rarely exceeds 1 second of arc, the largest P.M.s are near 10 seconds of arc. Given an annual P.M. of 1 second of arc, a star needs about 2,000 years to move one solar diameter in the sky. And the vast majority of P.M.s are smaller. Yet in the long run the P.M. gradually effects a complete change in the aspect of the heavens. This change is slightly retarded by the fact that some stars form groups; for instance, five of the seven

well-known stars of the Great Bear have the same P.M. in the same direction and consequently remain "lined up." *But yet after, say,* 20,000 *years our sky will have changed beyond recognition.*

This does not alter the fact that even now maps have been drawn on which the positions of the well-known bright stars tens of thousands of years hence are precisely indicated.

The Radial Proper Motion of the Stars

The radial P.M. of the stars (relative to the sun) can be determined accurately! This seems somewhat surprising. It is rightly considered as one of the finest triumphs of physical and astronomical science. If a star moves exactly along our line of sight and hence is not seen to move in the sky, we are yet able to measure its velocity accurately, and in all other cases the distance it moves towards us or recedes from us along our line of sight. The phenomenon that makes it possible for us to discover this movement and to calculate its speed is called Doppler effect.

The Doppler Effect

No doubt you will more than once in your life have travelled by railway and then have passed another train coming from the opposite direction. Now, engine drivers are in the habit of greeting one another by a signal of the whistle. This is not simply a formality or a friendly greeting, but a useful service regulation. Perhaps it will have struck you that the whistle of the other engine has a high pitch as long as it approaches, but that it becomes lower as soon as it has passed you, hence recedes from you. Yet you must not think that the whistle has two pitches. If you had been on the other engine beside the driver, you would have heard only one sound. The pitch of a sound, therefore, seems to be different according as the source approaches us or recedes from us. Thus every motor-horn has different tones. If the motor-car is stationary you hear its true tone; if it

approaches the tone rises, it being higher according as its speed is greater; if the motor-car recedes from us the tone falls, it being lower according as the car travels faster. The phenomenon is also easy to observe in the case of an aeroplane, especially when it flies low over our heads; the pitch of the drone of the motor falls perceptibly as the aeroplane recedes from us.

How can this phenomenon, which we all know from every-day experience, be explained? I think I cannot do better than ask you to solve the following problem: On a very busy afternoon, trains leave London for Croydon between 4 and 5 o'clock every five minutes, at 4 p.m., 4.5, 4.10, etc., up to 5 o'clock. In all thirteen trains. Each train covers the distance in exactly thirty minutes. I leave Croydon on the same day at 4.30 for London and arrive there at 5 o'clock. What number of trains from London to Croydon do I meet on the way?

Many readers will reason as follows: The journey lasts thirty minutes, the trains start every five minutes, hence I will meet *six*. But this answer is utterly wrong. True, someone standing on the line between London and Croydon will in the course of half an hour see six trains rush past him in the direction of Croydon. But my train leaves Croydon at 4.30 p.m.; at that moment the train that left London at 4 is just entering the station. Right, I'll leave that one out of account. My own train arrives in London at 5 o'clock, just as the 5 o'clock train to Croydon leaves the station. This train I will not count in either. But all the same, I will then have met eleven trains, namely, those leaving London from 4.5 to 4.55 inclusive. Nobody can deny that there are really eleven. The fact that I travelled to meet the source of the trains makes me meet them at smaller intervals of exactly 2½ minutes. Instead of meeting a train every 5 minutes I meet one every 2½ minutes.

Now what would be the effect if London did not send out trains but sound waves? In Victoria station an engine whistles; a sound wave flies along the line to Croydon.

The next wave does not start five minutes later, but very much sooner. But in principle everything is the same. If I am somewhere half-way on the line a certain number of sound waves will reach my ear (provided the sound is strong enough) in a given unit of time; if I move in the direction of the source (or, what comes to the same thing, if the source approaches me) the number of sound waves striking my ear in a given period is larger, hence the pitch of the sound will be higher. And reversely, if the source recedes from me, the tone will be lower.

But, I hear my reader exclaim, what has all this got to do with the radial P.M. of the stars? *A good deal*, as you will presently see. For however great the difference between sound and light may be, they have one fundamental characteristic in common: both are vibrations, sound being of the air, light vibrations of an electro-magnetic nature. And thus, if only I move with sufficient speed towards a source of light (or the light source comes towards me), the result will be that my eye, in the same unit of time, will be struck by a greater number of light waves than if I recede from the source of light (or that source recedes from me). The effect is now not a change in tone, but in *colour!* If the source of light recedes, the change is towards the red end of the spectrum; if it approaches, towards the violet end. In the spectrum of a star the Fraunhofer lines (*see* page 170) shift towards the violet if the star is approaching us, towards the red if it recedes from us.

In order to determine the speed at which a star is coming towards or is receding from us in our line of sight, we need but study its spectrum closely. We already know that the Fraunhofer lines have their fixed places in the spectrum (*see* page 170). A shift towards the left or to the right of these places is therefore easy to ascertain. To measure this shift is more difficult, so it should be done with great precision. But once we have come to know it exactly, it enables us at once to find the speed of the star relative to the sun with comparative ease. For, naturally, the extent of the shift

is dependent on the star's speed. You will also understand that a speed, if it is to have any appreciable effect on the colour of light, must be much higher than one which causes a change in pitch. In the case of sounds, a speed of 9 miles per hour is already sufficient; in the case of light, one of over half a mile per second is required.

Now, in dealing with stars, one should proceed with extreme caution. The Earth moves at a fast pace round the sun (the Earth's axial rotation may here practically be ignored). If at a certain moment a star is in the line of the Earth's motion round the sun, the Doppler effect must already be distinctly perceptible, even if the star has no radial P.M.[1] So this must be taken into account, which is always done in practice. For instance, the Doppler effect of a certain star is measured on two dates with an interval of six months.

Radial velocities of some 30 to 40 miles per second are generally found for the stars. The greatest thus far measured for any star is about 160 miles per second!

Spectroscopic Double Stars

So we have seen that the Doppler effect enables us to measure the radial velocities of the stars in a simple way. But it teaches us a lot more! In the first place it helps us to discover double stars: the *spectroscopic double stars*. There are, namely, a fair number of double stars whose components are so close to one another that even in the most powerful telescope they cannot be observed as separate bodies. But the spectroscope shows them up. The cause is not far to seek. One component will be receding from us for a certain period, while the other is just coming towards us. During such a period we shall then obtain a *double spectrum*. If, because one of the components is too weak, we can only obtain a spectrum of the stronger one, we shall not find a

[1] This particular Doppler effect at the same time affords us a splendid proof of the Earth's motion round the sun. Not only this motion may be proved by it, but also the Earth's speed in its orbit may be calculated from it.

periodic double spectrum, but a periodic *shift* in the spectrum. It is thus possible to calculate the period of revolution of a binary, of which neither component is visible, while only the spectrum of one of them is available! A large number of well-known stars, such as the Pole star, have proved to be spectroscopic binaries. It is but natural that it is precisely in the case of these double stars, whose components are so close to one another, that we find short periods of revolution (down to a few hours only) and vast orbital speeds. The visual binaries, that is, those double stars whose components are wider apart, so that they can be seen as separate bodies in a telescope, have lower orbital velocities as a result of their greater mutual distance. With those stars it will therefore be an exception if a shift can be observed in the spectrum as a result of their revolutions.

Axial Rotation of Planets and Doppler Effect

There is still more that the Doppler effect reveals to us. That we, at present, know the rotation velocities of some planets accurately, although there is nothing on their surfaces to mark it, is due to the Doppler effect. We study the spectrum of the light reaching us from one edge of the planetary disk, which approaches us as a result of the axial rotation, on the one hand, and that of the opposite edge which consequently must recede from us, on the other. In the case of the large, swiftly rotating planets, we can see a shift in the spectral lines, from which the rotation velocity can be deduced.

The Solar Spectrum and the Doppler Effect

But this by no means exhausts the honourable record of service of the Doppler effect. We examine the spectrum of the sunlight, but before it reaches the Earth's surface, it passes through the Earth's atmosphere. Here, too, absorption takes place, and our solar spectrum does indeed contain terrestrial lines, which occur in it because the gases of our

atmosphere have absorbed certain parts of the sunlight. But how are we to know that those lines are terrestrial ones and not *solar* lines? Again the Doppler effect comes to our aid! For does not the sun, too, rotate round its axis? True, it does so slowly, but the sun is so large that its left edge moves rather quickly towards us as the right edge recedes from us. We can see, if we successively examine the light of the left and the right edge, which of the spectral lines of the sun have shifted in consequence. Those are the *solar* lines. The *terrestrial* lines in the solar spectrum, of course, do not show this displacement. That is one way in which we are able, as we set ourselves to interpret the solar spectrum, to remove them as undesired intruders. The other way of identifying a terrestrial line is by its varying intensity. The terrestrial lines get much stronger at sunset when the sunlight comes to us through a much longer path of air than at midday.

The Doppler Effect and the Dimensions of Algol

And the Doppler effect has even helped us to ascertain the real dimensions of the famous star *Algol.* Algol is an eclipsing variable: a large, rather dark globe revolves round Algol exactly in the plane containing our line of sight and partly obscures it at set intervals. In a certain phase of the eclipse one side of the disk is eclipsed and we then receive light from the other side; in another phase conditions are exactly reversed. In the telescope we never see anything but the infinitesimal speck of light of variable luminosity; we observe nothing of a disk, let alone of a partial eclipse of it, but that does not alter the fact that, alternately, light reaches us from one edge and the other. If now Algol has axial rotation, which is *a priori* very likely, the Doppler effect must again be in evidence; the light of one edge is coming towards us, that of the other edge recedes from us. In the case of the Sun we can carry out the same test, as we saw above, by alternately covering one of its two sides. With Algol this is not possible and that is where its dark companion comes in useful.

It is indeed possible with Algol to measure the Doppler effect caused by its axial rotation and from this to calculate its rotation velocity. So we then know the speed of a point on its equator. But how can we now calculate its dimensions? Algol may be

small and rotate round its axis in a short time or it may be large and take a longer time to complete a rotation: this gives the same velocity. If, however, the duration of a complete rotation were known, we could at once calculate from it and the rotation velocity, the circumference of Algol. Now, this duration is not known at all . . . and yet it is known. For, Algol and its dark companion turn at a fast rate about their common centre of gravity. The duration of this revolution is accurately known and, in connection with the strong tidal force they must exercise upon one another, we can assume with certainty that the duration of an axial rotation is equal to that of a revolution of the dark companion round Algol. And now our problem is solved. The rotation velocity multiplied by the duration of one rotation (2 days 21 hours) gives the exact circumference of Algol, and hence also its radius. The latter proves to be 1,360,000 miles, more than three times that of the sun. It is the astronomers Rossiter and MacLaughlin who evolved and applied this method.

Axial Rotation of the Stars

The Doppler effect is a very useful thing indeed! Quite recently Carroll evolved a method by which the axial rotation of a star can be calculated from the "contours" of the Fraunhofer lines. The reader will be able to understand the principle of this method if he considers that—quite apart from the radial P.M. of the star—a portion of the light we receive from the star is emitted by a part of the star approaching us, another portion by a part of the star receding from us. The spectral line will consequently be less sharp, vaguer, than in the case of a non-rotating source of light. From an investigation extending over some hundreds of stars, rotation velocities (at the equator) ranging from 15 to 150 miles per second have been found. A velocity of about 60 miles per second seems to occur most frequently. There is still much here that is uncertain, but at any rate an interesting new method of investigation has been discovered.

CHAPTER IX

THE MILKY WAY OR GALAXY

Now that we have learnt a number of particulars concerning the stars, the question arises as to whether those hundreds of millions of stars form a definite structure, a stellar system. In other words, have we to do with hundreds of millions of unrelated units, scattered at random, or do those units really constitute a system, so to speak, in the same way as the planets form a distinct planetary system?

Is there a higher unity by which the stars are arranged and combined into groups?

Constellations

The Ancients already tried to group the stars. They combined them into Constellations, which were fancied, rightly or wrongly, to show the imaginary outline of animals, inanimate objects, mythological heroes and demi-gods or goddesses. There is no deeper sense in these combinations. The outlines of a given constellation are perfectly arbitrary, yet tradition is so strong that the old names have been maintained to the present day. Nowadays the constellations are useful, in that they can be employed as we do the names of the streets in a town, just to locate ourselves. If you know the constellations and if you can find them in the heavens, you will have little difficulty in tracing a comet, for instance, whose position in a certain constellation is known. You can find a certain person in a town most easily if you know the street where he lives. But again—the names of the constellations convey no deeper sense. The stars forming them do not belong together at all. They only

happen to be seen *by us* in the same direction. The combinations are merely perspective ones. In 50,000 years' time they will have disappeared, as groups, without leaving a trace. So these constellations are devoid of any deeper sense. Still, it is convenient to know them. A number of books contain excellent descriptions of them; there are splendid star maps, also for the use of amateurs. We shall not here repeat these descriptions, which have been given over and over again.

What we do want to say is that most of the very bright stars also have proper names, which as a rule are of Arabic origin. The other stars visible to the naked eye are generally indicated by a Greek letter and the name of the constellation; for instance, star δ of the Lesser Bear.

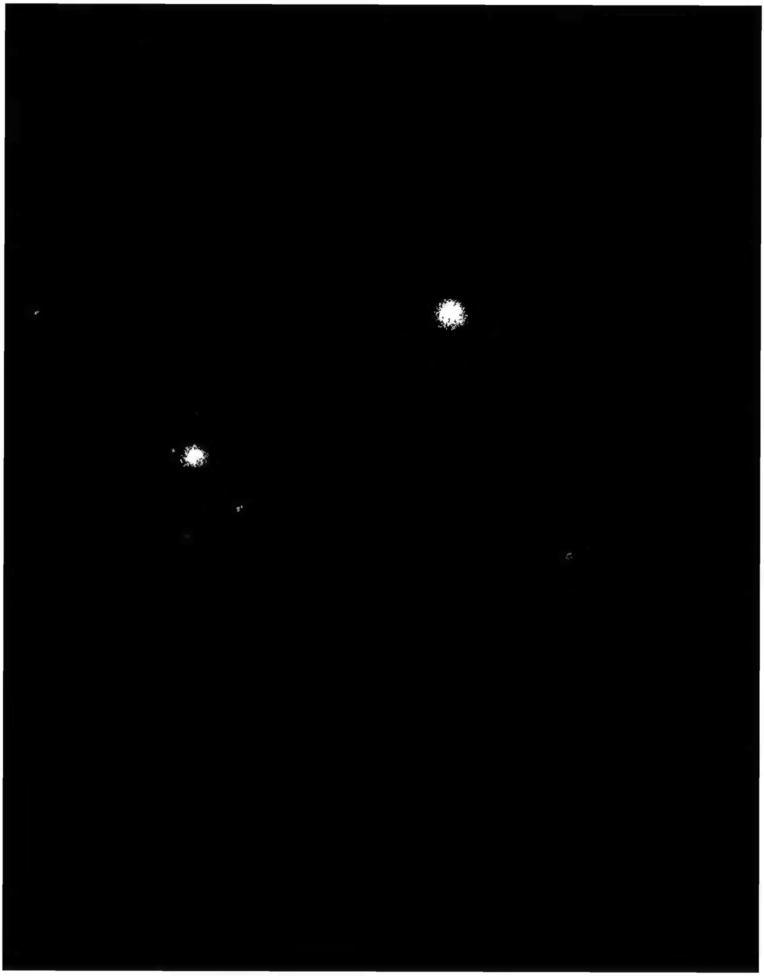
Of late years it has been established as a fact that there are a few, not many, exceptions to the purely arbitrary nature of the constellations. Thus most of the stars of the Pleiades really belong together; so do five of the seven stars of the Greater Bear. Curiously enough, some stars of other constellations also belong to the latter group.

We must now take leave of our constellations, if we want to devote ourselves to our inquiry as to whether there is any order and regularity in the stars, or, in other words, whether there exists a real *stellar system.*

The Milky Way or Galaxy as Stellar System

The first astronomers who seriously envisaged this problem and also arrived at a satisfactory solution, were the Herschels, father and son: William (1738–1822, who discovered Uranus) and John (1792–1871). They discovered the Milky Way as such, and found that all the stars we see as stars (the nebulæ will be dealt with in the next chapter) form part of the Galactic system. So also our sun. *Our sun is a star of the Galactic system.*

The Milky Way was already known to the Ancients. On bright moonless nights you can see—in Great Britain best in the summer months—the Milky Way stretch as a



PART OF THE GALAXY NEAR THE SOUTHERN CROSS
(*From Jeans*).

white belt across the entire vault of heaven from horizon to horizon. Far from the light, the smoke and soot of the town you can see and enjoy it as one of the finest spectacles in the sky.

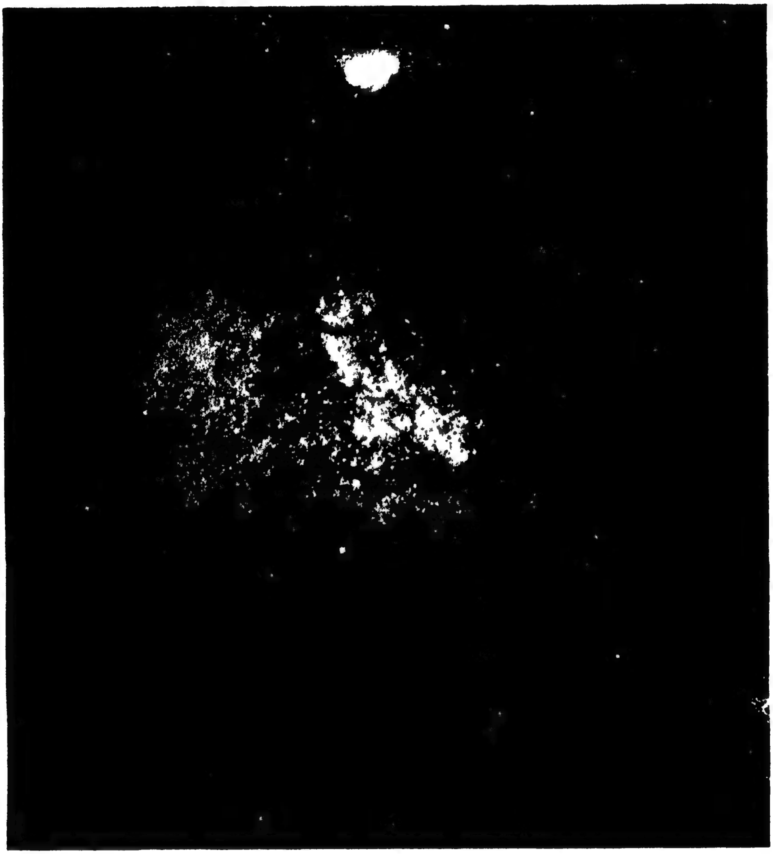
The Ancients had a myth to account for its origin, saying that the maternal milk of Juno, wife to Jupiter the Supreme god, had splashed against the firmament and left the white track of the Milky Way. By the way, Milky Way is by no means an inappropriate name: what we see is a milky white track; *we cannot, with the naked eye, observe any separate stars in it.*

So long as we do not direct a telescope to the Milky Way, we might easily suppose it to be a real nebula. There are nebulæ that do not consist of stars, but of inconceivably rarefied gaseous masses taking up tremendous vastnesses in space. One of these nebulæ is visible to the naked eye in the constellation Orion.

But even a small telescope reveals the secret that the Milky Way is composed of stars, which, seen from the Earth, almost seem to touch one another. Even Galileo was able to see this through his primitive instrument.

If we go to the Southern hemisphere we also see the Milky Way, that is to say, its other half. So it seems to surround us like a gigantic belt. This alone might lead us to suppose that also the ordinary stars, which we see about us in all directions, form part of the same whole.

But there is more. This the Herschels already realized. We have seen that the stars are not distributed regularly in all directions about us with a mean density, but that they show a certain thinning out (*see* page 287). We found that particularly the number of faint stars, which are as a rule *farther* away from us, is much smaller than would follow from a homogeneous distribution in all directions. What on further inquiry proves to be the case? The brightest stars, which may, generally, be assumed to be nearest, occur in all directions with almost equal frequency. But this by no means holds good for the fainter stars, which may on



Part of the Galaxy, in Sagittarius.
Photo: E. E. Barnard, Yerkes Obs.

an average be considered as being farther away. In a telescope you see an *increasing* number of faint stars as you approach the Milky Way. And this applies most strictly in the case of the faintest, hence also remotest stars, which are practically confined to the plane of the Milky Way, or galactic plane! The number of stars seen simultaneously in a telescope, therefore, increases as you direct your telescope to a point nearer to the Milky Way. And this rule holds

good with almost mathematical exactitude. As the climate on Earth is dependent on the degree of latitude, so the number of stars we see in a certain part of the sky through a telescope depends on the number of degrees of arc which that part of the heavens is away from the Milky Way. This rule even holds good to a certain extent for the naked eye. Let an astronomer have a look at the field of a telescope without knowing in what direction it is pointing, and he will at once be able to tell you approximately how many degrees of arc it is from the Milky Way!

All these facts are indicative of the form of the Galactic system; it is a *disk*, a rather flat disk. If we are somewhere in the middle, or—to put it more generally and correctly—somewhere in that disk not too close to the edge, it will be clear that if we look in any direction *in* the plane of the disk, we must see innumerable stars and that *all* remote stars must be seen in that plane. But if we look in a direction at right-angles to the disk we shall see much fewer stars and exclusively rather near ones. In all directions, in the plane of the disk, the Milky Way will be seen by us, from which it follows that it must surround us like a ring. This, in a simple and natural way, explains how we observe the Milky Way and its stars. The Herschels thought that our sun was very close to the centre of the disk. This has since proved not to be correct. It seems that the sun is even nearer to the edge than to the centre of the disk.

The Milky Way, then, as seen from the Earth, stretches as a luminous belt across the sky. In places it seems to consist of two stripes, separated by a dark space. The Dutchman Pannekoek has shown that at those places there are cosmic clouds, dark nebulæ, preventing us from observing the galactic regions behind them. The Dutch astronomer Kapteyn, too, has contributed largely to our knowledge of the Milky Way. Many hold the opinion that the Galactic disk is built more or less spiral fashion.

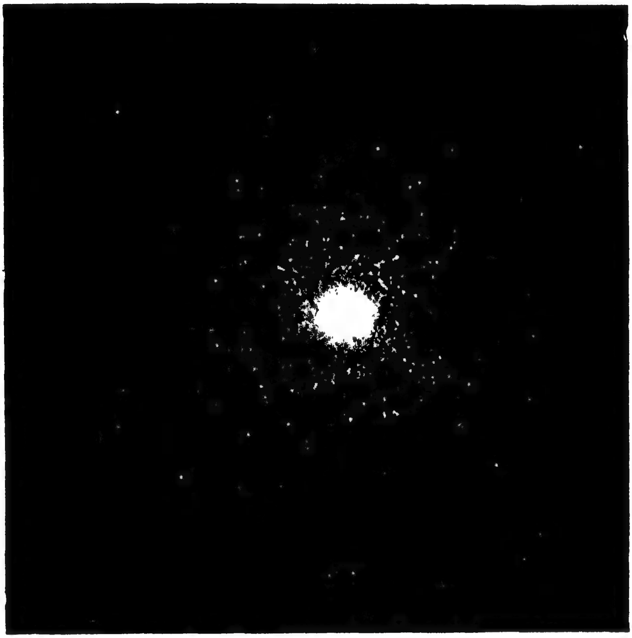
There is yet another thing supporting the disk-theory, notably the fact that we can observe innumerable other

Star Clusters. Globular Clusters

Before entering into further details on the Milky Way as revealed by the investigations of the last few years, we must first go down a side-track. If we search the heavens with a telescope, we see at many points congeries of stars, called star clusters. We distinguish in the first place open star clusters, an example of which is afforded by the Pleiades. These open star clusters number some hundreds or thousands of stars. Besides these we also know globular star clusters. These are very remarkable bodies; as the name tells you they are shaped more or less like a ball or globe. Almost a hundred of them have been discovered, of which about five can be observed with the naked eye as faint "stars." But this seems to exhaust their number; no new ones have been discovered for years; so it may be assumed that there are no more. They all have about the same form and only differ in size. Each cluster consists of some tens of thousands to hundreds of thousands of stars. A few of the clusters contain Cepheid variables from which the distance of the cluster may be determined, and the distances of the rest of the clusters have been determined by ingenious methods by the American astronomer Shapley. The distance for the nearest clusters proves to be about 20,000 light-years, for the remotest clusters about 200,000 light-years. Jeans, in stating the latter fact, very aptly remarks that the Cepheid method is a good deal simpler than a parallax determination.

For the parallax of one of the stars of the very remote clusters is about as large as the radius of a pin's head at a distance of 4,000 miles.

Shapley has accurately indicated the places of these globular star clusters. It transpires that they are arranged symmetrically on either side of the Galactic plane, to a distance of about 50,000 light-years from that plane. Jeans



GLOBULAR CLUSTERS IN HERCULES.

makes the following ingenious comparison: take a round currant bun, split it into two parts in the usual way, so as to obtain circular cross-sections. Now butter the bun freely and put the two halves together again. The butter then represents the stars of the galaxy; the currants in the bun are the globular clusters and the dough itself must be thought away. Our sun is about in the middle of the layer of butter, that is to say, it has as much butter above as

below it, but it is probably nearer to the edge than to the centre of the buttery disk.

We shall now take leave of this appetizing picture of the Milky Way and return to reality. The Milky Way, then, is a disk with the globular star clusters grouped close around it. In some parts of the Milky Way we can observe local congestions of stars: they are there somewhat closer together than is seen, on an average, in the Milky Way. In other stellar systems (nebulæ), too, such local congeries occur.

Rotation of the Galactic System

The latest investigations have proved indubitably *that the whole disk of the Milky Way rotates round an axis.* This had long been supposed to be so, for it can be proved by the laws of mechanics that if there were no rotation, all stars of the Milky Way would tend towards the centre and there conglomerate into one big mass. This rotation has now also been confirmed by observation. So we can consider the disk as a wheel, but this conception is slightly misleading, because when a wheel rotates the outer parts move faster than the inner ones. And this, in the case of the Milky Way, is decidedly *not* so. Here, too, the law of universal gravitation is in evidence, in such a way that the innermost stars attract, as it were, the outer ones as one mass. Hence, the farther the stars are from the centre, the slower their motions, in the same way as in the solar system according to Kepler's third law. Therefore, the best plan is to conceive the Galactic disk as a disk of particles of matter in which the outermost revolve slowest around the innermost; the closer you get to the centre, the swifter their rotation. Our sun is at about 35,000 light-years from the centre of the disk. The greatest length of the disk may be estimated at about 100,000 light-years, its thickness at six to ten thousand light-years. It should not be forgotten that the disk will probably be thicker in the middle than at the edges. At the point where our sun is, a complete revolution lasts about 200 million years. The sun travels at the rate of about

200 miles per second in its orbit, in relation to the centre of the disk!

Mass of the Milky Way

Arrived at this point we may venture to give an estimate of the total mass of the whole Milky Way. It will be seen that such an estimate may become possible once the rotation velocity of the disk at some given points has been determined. This has, in fact, been done, and then it transpired that the mass of all matter within the sun's orbit is sufficient to form some 100 milliard stars of average mass.

It must here be emphatically pointed out that this is the result of investigation and discoveries, truly revolutionary discoveries, of the last few years. We have here to do with calculations that are among the most difficult imaginable. Added to this, it seems to have been definitely established that the loss of light, owing to absorption, not only in the dark nebulæ but also elsewhere in the Milky Way, may by no means be ignored. Needless to say that it does not exactly simplify the calculations. There is no astronomer who claims his figure to be quite true. There may be 100 milliard stars in the Galactic system, there may be twice that quantity. The only thing they are certain of is the order of magnitude. There cannot be ten times as much or ten times as few, not even three times as much or as few. Nor is the place of the sun in the disk accurately known. The coming years, or if you like decades, will have to provide us with the exact figures.

And after some centuries we trust that people then living will be as familiar with the Galactic system as we are with our solar system. A solar system on a gigantic scale. On a scale hundreds of million times as large!

The number of stars in the Galactic system cannot at present be given more accurately than our estimate of between 100 and 200 milliard. About one per cent. of those stars can be observed in our largest telescope.

Do not think that these well-nigh infinite numbers of stars

are close to one another. In some places their mutual distances may be estimated at five or six light-years. The more usual distance between stars in the Milky Way is, however, appreciably greater: thirty to forty light-years.

I can easily sympathize with a reader who says that he now thinks his Universe large enough. A hundred milliard stars, 100,000 light-years in diameter; it seems more than sufficient. But we must again warn him that we are only at the very *beginning* of our voyage into space: we are still at home! We are still in *our* stellar system, where our *sun is one of the children.* We have now some idea of one home, our own home. But we shall see that there are many millions of other homes in the Universe.

CHAPTER X

THE NEBULÆ—OTHER STELLAR SYSTEMS

If you search the heavens with a small telescope you will observe, in quite a number of places, nebulous little stars or patches. With the naked eye, two of these cloudy patches may be observed, round star θ of the constellation Orion and in Andromeda just above star μ.

The nebulæ may be broadly classified into four main groups:

1. Patches, which, when strongly magnified, appear to be no nebulæ but star clusters. These we have already discussed.
2. The planetary nebulæ. The term is unfortunate, for these nebulæ have nothing whatever to do with planets. There are some hundreds of them. They all belong to the Galactic system and consist of one star which —though we do not know how—has wrapped itself in a mantle of gas.
3. The gaseous nebulæ proper.
4. The extra-galactic nebulæ. These are veritable stellar systems, sometimes in the form of a spiral, in which case they are also called spiral nebulæ.

Gaseous Nebulæ

The gaseous nebulæ proper appear as splendid, fantastically shaped objects in the large telescopes. The nebula in Orion, which is visible to the unaided eye, belongs to this class; if we look through a powerful telescope we see that

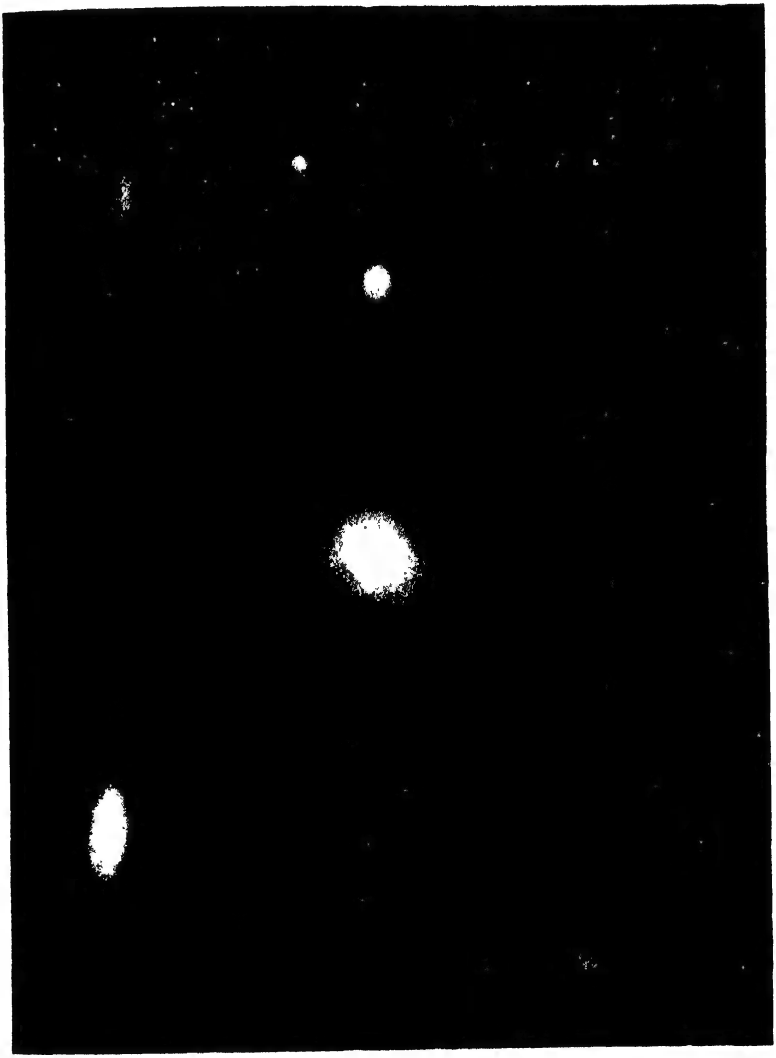
this nebula extends over the whole constellation Orion and is only denser round the star θ Orionis. These gaseous nebulæ are of almost inconceivable tenuity. The Pleiades, too, appear to be enveloped in such a nebula. Presumably these nebulæ are nothing but local condensations of incredibly tenuous gas clouds that fill up all interstellar space of the Milky Way. These gaseous nebulæ are at any rate situated *in our Galactic system* and, *in* a certain sense, *form* part of it. Wherever they are a little denser in the vicinity of bright stars, they are illuminated by those stars.

We have only discussed these nebulæ and the planetary nebulæ for the sake of completeness. We now come to the real subject matter of this chapter: the nebulæ that are really stellar systems, hence the fourth *class.*

The Stellar Systems

Astronomers have long waged war over the real nature of these nebulæ, until our most powerful telescope on Mount Wilson once and for all revealed their secret and removed the cloud that had until then enveloped them. Photographed in this telescope they appeared—at any rate those nearest to us—to consist entirely or almost entirely of stars, hundreds of millions of stars. There proved to be, far away in space, other stellar systems similar to our own stellar system, the Milky Way. Far, far away there were other worlds!

The nebula in Andromeda, visible to the naked eye just above star μ of this constellation, is such a stellar system. It presents a brilliant spectacle in the Mount Wilson telescope, as you will see in the photo opposite. It is as if we see the Galaxy itself before us. The structure of the Andromeda nebula is the exact replica of that of our own stellar system as we have deduced it by observation and calculations. We need not have a moment's hesitation; here is a stellar system that in every respect may be put on a level with our own.



THE NEBULA IN ANDROMEDA.
Photo: Yerkes Observatory.

The Mount Wilson telescope shows us many stellar systems, no less than about *two million.*

The reader will now, naturally, be desirous to know the exact distances of these systems, their dimensions, the number of stars they contain, their distribution in space.

But here we are faced with a difficulty. Until quite recently the answer to all these questions seemed rather obvious; of late, however, fresh doubts have arisen.

We will now first expound the theories which, until a very short time ago, were universally accepted. After that we shall deal with the very latest developments.

The nebula in Andromeda is the stellar system nearest but one to us. Somewhat nearer is another stellar system in the constellation Triangle.

The distance of the Andromeda nebula, determined by the luminosity of certain objects in that nebula, was generally accepted to be 900,000 light-years. That of the Triangle nebula as 850,000 light-years. The other nebulæ are fairly evenly distributed through space at intervals which were estimated at one to two million light-years. The farthest whose distance could be determined were estimated to be 140,000,000 light-years away.

We said just now that the stellar systems are fairly evenly distributed through space, but we should have added, barring some centres of aggregation. Thus there are, for instance, no less than 300 in the constellations Virgo and Coma Berenices.

Those distances were determined as follows. When, in the same way as for the nebula in Andromeda, the distances of the near-by stellar systems had been found, the American astronomer Hubble discovered that stellar systems of a given shape (these shapes will be discussed later) *all have the same luminosity.* Hence the difference in brightness of stellar systems of the same form is exclusively due to difference in distance. This enables us at once to deduce the distances of very remote stellar systems from their brightness. Let

us illustrate this by means of an example. Suppose that we have found by a direct method that a given stellar system is two million light-years away from us. Now we observe another stellar system (of the same form on a reduced scale)—in which no separate objects are distinguishable owing to its remoteness—that has a brightness of $\frac{1}{25}$ of that of the first-mentioned system. The latter system must then be at five times the distance of the former, hence at ten million light-years (for the light-impression decreases as the square of the distance).

The masses of a number of stellar systems were determined in the following way.

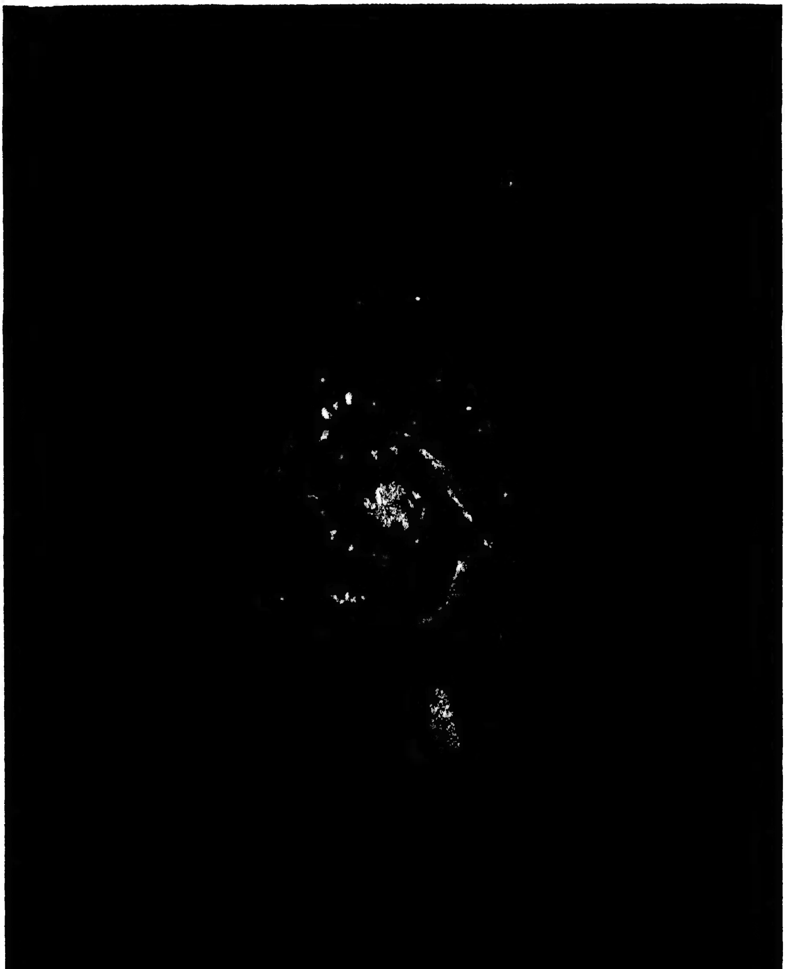
Like the Milky Way, the other stellar systems, too, must rotate round an axis. Otherwise they could not continue as such. Thanks again to the Doppler effect this axial rotation was proved for a number of them. The method is by now familiar to you: first the velocity is measured with which one edge of the disk approaches us, then that with which the other edge recedes from us. This gives us the rotation velocity. From this value the total mass can be deduced. And since the mean mass of a star is known, we can also approximately find the number of stars in the nebula (or, at any rate, the number of stars that might be formed from its total mass).

The distances and hence the dimensions and the masses of the stellar systems had thus been established. They all proved to be of the same order of magnitude. Their diameters were about 10,000 light-years; their masses were of the order of two to three milliard stars!

Respectable bodies, no doubt, but yet all of them far inferior in size to *our* Milky Way, *our* stellar system, for which we have found a diameter of 100,000 light-years, and at least 100 milliard stars.

Size of the Milky Way and of other Stellar Systems

Here was a puzzle! According to the values found our Milky Way was the one exception among millions of other-



THE NEBULA IN THE CANES VENATICI.
Photo: Mount Wilson Obs.

wise similar stellar systems. There was a period in the history of human thought when such an exception in our favour would have been accepted as a matter of course. To those who hold that the Earth takes up a privileged position in the Universe, the fact—that the stellar system to which our sun and hence also our Earth belong proves to be an extraordinary stellar system—does not come as a surprise! On the contrary, such a thing is then quite natural. But modern thought takes quite a different view of the matter. If among millions or perhaps milliards of stellar systems there is one that proves many times larger than all others, modern man already thinks this queer; he is not prepared to take it at face value, and he will try to find a reasonable explanation for it. But that it should be precisely his own stellar system that is exceptional is quite unacceptable to him. It may safely be said that there was not one astronomer who considered the results arrived at with regard to the Milky Way and the stellar systems as definite.

Now, quite recently, facts have come to light that seem to point a way out of the existing dilemmas. In the first place, as we saw above, serious doubts have arisen as to the correctness of the method employed for measuring the distances of the nebulæ. For, in the end the whole scale of distances is entirely dependent upon the small number of distances found by direct means, for the determination of which astronomers started from the luminosity of a number of objects that were taken to be separate stars. Not long ago, however, De Sitter pointed out that these objects are possibly no stars, but star clusters. If his conjecture should be confirmed the real distances may be even ten times as much as those accepted hitherto! This would lead to quite different dimensions for the stellar systems, which would then prove to be of the same order of magnitude as our Milky Way. A second consideration comes to support this supposition. Hubble succeeded in proving the presence of about 140 globular star clusters in the nebula of Andromeda. This number is of

the same order of magnitude as that of the globular star clusters present in our Milky Way. But if the estimated distance of 900,000 light-years be correct, they must without any exception be smaller than the globular star clusters in our Milky Way. Now this is highly improbable. It is far more likely that the distance so far accepted is too small.

Very recent investigations (by Stebbins, 1934) also cast a doubt on the correctness of the mass determinations. These values, too, seem to be much too low. Stebbins evolved a new method of determining the diameter of the nebula in *Andromeda* by means of a photo-electric cell, which betrays the presence of light-rays by an electric current generated by them. By this method light can be detected that is too *weak to make an impression on the retina of our eyes or even on a photographic plate!* It now transpired that the Andromeda nebula must extend over an area twice as large as had until then been assumed. This need not surprise us. It is, for instance, an open question whether regions near the edge of the galaxy could be observed, at a distance of a million light-years, by the human eye, aided by telescopes as we know them at present. If Stebbins's results are correct, it at once follows that the determination of the mass, as hitherto carried out, is erroneous and bound to give far too low figures.

All this will have to be further gone into in the years to come. Once the new super-telescope is ready, a definite answer will soon be given. Personally, I strongly incline to the belief that the stellar systems and our Milky Way will ultimately prove to be of the same order of magnitude.

What we are already certain of is that the stellar systems contain enough matter for milliards of stars. But not all these stars have yet been formed. In some systems nearly all stars have definite forms; other systems only have stars at their edges while the centre still consists of uncrystallized matter; yet other systems are entirely composed of shapeless

matter. We shall revert to this in the last chapter. Here we shall confine ourselves to stating the fact that some stellar systems are globular, some a little flattened, still others a little more flattened, until we come to systems that have entirely acquired the form of a flat disk or spiral. The flatter the system the larger its diameter and the further the formation of separate stars has progressed.

CHAPTER XI

THE UNIVERSE

Two million stellar systems, each numbering milliards of stars, or, at any rate, containing enough matter to form milliards of stars! That together makes thousands of billions of stars, some millions to each inhabitant of the Earth! We are getting richer and richer! Yet there is not a single reason to suppose that herewith we have reached the "end" of the Universe. On the contrary, it is certain that our eye is incapable of penetrating to a great many worlds. For in the Mount Wilson telescope many stellar systems are on the border-line of visibility—there are more remote than nearby systems. There has as yet not been any sign of "thinning out"—the mutual distances are, on an average, the same everywhere. There is, therefore, every reason to assume that, when in some years' time the new super-telescope will be mounted ready for use and we shall be able to search a part of the Universe twice as deep as we can in the Mount Wilson telescope, the number of visible stellar systems will be eight times as large. Eight times—for we can then search a celestial globe whose radius is twice as large and hence has eight times the volume of the present one.

A question of very, very great importance now arises. Does this go on infinitely? Will each greater telescope make us see an ever-increasing number of stellar systems; will it transpire in the end that some milliards of stellar systems constitute one *gigantic super-system* and are we then to discover new super-systems? Ever more? And so on, and so on?

Formerly this was certainly the generally accepted view. Kant, the great philosopher, already advanced a theory to

this effect. And how could it be otherwise! For here man was faced, be it in another, higher form, with the same problem as that treated in the first chapter concerning the Earth's surface.

People were unable to conceive the Earth's surface as finite, yet to conceive it as infinite seemed equally strange.

As we saw, until a few years ago we were up against the same difficulty in regard to the Universe. Was there indeed waste and emptiness beyond the last stellar system? Emptiness, infinite and unbounded? It was unbelievable. It was then even better to assume that stellar system followed upon stellar system in infinite succession and to all eternity, although such infinity was equally unintelligible to finite beings such as we are. It would then, at the same time, have to be admitted that we only possess and could never aspire to anything higher than knowledge of an infinitesimal part of the Universe, a part so insignificant as to be without dimensions, a mere speck in the vastness of the Universe.

But why, then, did not the firmament appear as one dazzling white dome of light emitted by one huge conglomerate of stellar systems? (*See* page 288.) Perhaps there were dark cosmic clouds precluding the eye from penetrating to the remotest depths of the Universe. This, at least, was a way of accounting for the black hue of the sky.

So the Universe was generally accepted to be infinite, an endless world in which stellar system followed upon stellar system.

Until Einstein appeared on the scene and his relativity theory opened up new, unexpected vistas.

We saw in the opening pages of this book that the problem as to whether the Earth's surface is finite or not was solved as soon as people realized that like a curved plane it bends back upon itself, that it is boundless yet not infinite. In the same way the relativity theory teaches us that the *Universe, too, bends back upon itself, hence is unbounded but finite.* At least, that it *may* be like this.

It is hardly feasible to give a popular exposition of this

theory. We saw how the theory of the curvature of the Earth's surface ran counter to the generally accepted views and hence how difficult it was to many to familiarize themselves with this new conception. And this applies with even greater force to the theory of the bent, the curved, world space. It is generally received with a kind of instinctive resentment which is very difficult to conquer. The fact that it is impossible to give a complete, yet popular exposition of the relativity theory further complicates the dilemma. For a complete understanding a higher mathematical training is essential.

Yet we feel it our duty to make these fundamental concepts somewhat clearer to the reader. We shall consequently *endeavour to give such indications as will enable him to get* somewhat nearer to a possible solution of these mighty problems.

The Straight Line in Space

Let us start on our way. Inhabitants *of the* Earth *moving on its surface* in a certain direction, *think they travel in* a *straight* line. That is exactly why they are unable to imagine that, while continuing to travel in the same direction, they will finally return to their point of departure. And yet this proves to be the case. Has now their path not been straight? The reply must be: straight and not straight, that depends on how you look at it. Certainly straight if referred to the Earth's surface, but curved in space.

Now we are going to travel by a straight path, a straight line in space. But how are we to know if we really follow a straight line in space?

This question is certainly not easy to answer. Yet a simple carpenter solves the problem if he wants to see whether a board is perfectly straight. Perhaps you will say that he uses a square to satisfy himself that the board has been planed straight. This he can only do if he is quite sure that his square is straight. So in this way we do not get any further. But our carpenter is not at a loss for another

expedient. Should he doubt the straightness of his square, he will very wisely resort to a simple and natural expedient: he will hold the square on a level with his eye and look along its edge. He can then see whether his square is straight or not.

Let us look into this a little more closely. What does our carpenter actually do? He verifies whether the ray of light emitted by the other end of the square's edge reaches his eye by travelling exactly along the edge. In other words: he works on the supposition that *a ray of light follows a straight line*, that is to say, follows a straight line so long as there are no special circumstances to break it. Our carpenter will never make his test with one half of his square immersed in water!

So we now *think* we can safely say that a straight line is the path taken by a ray of light in a medium that gives no rise to refraction. The air-free space of the Universe may in this respect be considered as an ideal medium.

And then Einstein suddenly came along with his bold assertion that *the path of a ray of light is curved!*

That we have here to do with an extremely slight deviation is obvious. Otherwise this Einstein effect would have been discovered long ago. Practically the Einstein effect is not observable until a ray of light, in its path through space, passes near the edge of a heavenly body exerting a mighty gravitational pull, e.g. when a ray of light which comes to us from a distant star passes close to our sun. Then, according to Einstein, the ray of light must be slightly bent by the gravitational force of the sun, so that the apparent position of the star will, in perspective, be slightly farther from the sun's edge than it really is. In short, the stars which, seen from the Earth, are near to the sun in the sky, must have apparent positions a little farther from the sun's edge than their actual places.

But why does it follow from the relativity theory that a ray of light under the influence of gravitation describes a curved path? What has a theory, which in its deepest sense merely denies the existence of absolute motion and

absolute rest, to do with the path of a ray of light in a gravitational field of force? We shall try to make this clear, too, by means of an example furnished by Einstein himself.

Mr. Jones in Space

Mr. Jones is "somewhere in space," in a room closed on all sides but properly lighted. The only thing he knows is that he is somewhere in space. There are quite a number of objects in his room. These are on the floor or on tables, or in cupboards or are suspended. Jones paces his room and it costs him an effort to jump up in it. Whenever he tries to lift a chair or a table from the floor, he only succeeds at the cost of considerable exertion. If he takes up an object and lets go his hold on it, it drops to the floor of his room. Jones has a number of very delicate instruments at his disposal and by means of them he is able to ascertain that the objects fall with what is called uniformly accelerated motion! After the first unit of time has elapsed they have dropped 1 cm., after the second unit in all 4 cm., after the third unit of time in all 9 cm., and so on. This is how objects fall under the influence of the gravitational pull of a heavenly body.

Now what is Jones, locked away in his solitary room, unable to get even a glimpse of the outer world, to infer from these phenomena? Presumably he will arrive at the conclusion that his room is on the surface of some heavenly body, or that it is suspended by powerful cables from some crane above the surface of that heavenly body. In other words: all physical phenomena described will probably be attributed by Jones to the attractive force of a heavenly body, or, in other words, to what is called gravitation. Besides, he assumes that his "cabin" is neither receding from that heavenly body nor approaching it, so that he is at rest in relation to it. That is exactly why Jones found that the laws of falling bodies applied with perfect accuracy.

But does this prove his hypothesis? Can he be sure that his supposition, which gives a simple, natural explanation of

the phenomena observed by him, is indeed correct? Is there no other explanation possible? Jones thinks it over. What other explanation might be conceived for the physical phenomena of gravitation and fall occurring around him? Could these phenomena possibly be due to another cause than gravitation? Jones, after some thinking, must at least admit the possibility. He is not now concerned with the degree of probability—this, in principle, is immaterial. Jones can imagine that he is at an infinite distance somewhere in space, practically speaking outside the attractive pull of any heavenly body, and that his room is pulled upwards by some force which continually increases its speed, hence is of uniformly accelerated speed. Given a specially constructed rocket fitted somehow to the cabin, this might be conceivable. Jones, too, must come to the conclusion that his explanation, improbable though it be, may not be rejected altogether. All phenomena occurring in his room can be equally well explained on this assumption: objects released must seem to fall at ever-increasing speed, an object lying or standing on the floor must exert a pressure on it, and so on. Everything occurs in exactly the same way. But if the rocket theory is the right one, we have to do with phenomena not of gravitation but of *inertia*.

So the same phenomena prove to be equally well explainable from the effect of gravitation as from the laws of inertia. This is Einstein's famous *principle of equivalence.*[1]

Need we go any further into these inertia effects? Everybody is familiar with them from daily experience. Let me give an example very much like the one given above.

If I am in a lift that begins to ascend or that accelerates its upward speed I feel my body being pressed more firmly on to the floor of the lift, so that the force of gravity is, as it were, increased. An object dropped from my hand would reach the floor of the lift sooner than otherwise.

On the other hand, if the lift begins to descend or

[1] Newton, too, was already conscious of the close relation between heavy and inert mass, and—vainly—tried to find an explanation for it. The relation, nay, identity, follows direct from the relativity theory.

accelerates its downward speed I seem to feel lighter; an object would seem to fall more slowly.

The phenomena occurring in Jones's room appear to follow equally well from the effects of gravitation as from those of inertia. We here begin to see a possible way to liberate the force of gravity from its isolated position and to establish its relation to other natural forces. That is what Einstein has actually done. But we shall not follow him further in this direction.

We return to Jones's cabin somewhere in space. And we hear Jones wondering again whether there is any possible way of concluding definitely which of the two explanations meets his case. At that moment he is startled by a sudden noise! A hole is struck in the right wall of his room. A rifle bullet pierces it at great speed, hits the left wall, makes a hole in that, too, and vanishes. Jones looks through the holes, but sees nothing but darkness. So that does not help him either. And then a sudden idea flashes through his mind: what he can do is measure the height of the right and the left hole. He has very accurate measuring instruments at his disposal. The hole in the left wall proves to be slightly closer to the floor than that on his right, and now Jones thinks he is near to a solution of his problem. For, it has taken the bullet some time to traverse the room from right to left; so if his room is indeed pulled upwards by a rocket the hole on his left must be lower than that on his right side by exactly the distance his room has travelled upwards while the bullet traversed it (assuming that the bullet was fired in a direction parallel with the floor of his room). Accurate measurements show that the left hole is exactly as much lower as Jones might expect at the speed of a bullet. So now he considers his problem as disposed of: apparently his room is after all pulled upwards, so that what he observes are the effects of *inertia*. But then all at once Jones sees that he is a fool to think so! For exactly the same would have happened under the influence of gravitation. A ball fired on Earth does not describe a

horizontal path either, but is slowly pulled towards the Earth, falls at the same time. We are all familiar with this phenomenon! (*See* page 96.)

So again Jones is faced with the same dilemma. Gravitation or inertia? He sees no way out of it. There is still one course open to him! There are now holes in his room. And through one of them he at last sees something, a star. He stops the other hole and now proceeds to make a very difficult test. What he wants to do is to carry out an extremely delicate experiment with a ray of light coming from the star outside and entering his room through the hole. Light travels at an extremely fast speed, but still it takes a ray of light some time to pass from one wall to the other. In this infinitesimal space of time his room, if it is indeed pulled upwards by a rocket, will have slightly risen. The point where the ray of light strikes the left wall (it reaches him exactly horizontally, parallel to the floor of the room) must then be a trifle, be it ever so little, lower than the point exactly opposite the one through which the light entered. Exactly as in the case of the bullet. Only, owing to the terrific speed of light, the difference will be infinitesimal. Fortunately Jones has exceedingly fine instruments at his disposal, which enable him to ascertain the difference. It squares exactly with the distance his room, if it is being pulled upwards, must have travelled in about a hundred-millionth part of a second, that is, the time it took the ray of light to traverse his room.

Now Jones is where he wanted to be. He has now proved that his room is pulled upwards by a rocket at uniformly accelerated speed. For a ray of light can—such is his conviction—undergo no gravitational influences. He has now ascertained that the point on the left wall hit by the ray of light is lower than that on his right where the ray entered his room; so there is no choice. His room is not at rest, is not under the influence of the attractive force of a heavenly body, but his room moves at uniformly accelerated speed in space!

Jones has therefore succeeded (at any rate thinks he has succeeded) in solving the problem of absolute rest or motion for his room. He thinks he has now shown indubitably that his room is in motion. But his proof entirely rests on the assumption that the path of a ray of light, unlike that of a ball, is not curved by gravitation.

What is this supposition, this hypothesis, based on? Jones will have to think long before he can give a reasonable answer to this question. He will not even be able to give an answer at all. And yet Jones *proves* his room to be in absolute motion in space on the strength of that very hypothesis!

The theory of relativity denies the existence of such a thing as absolute motion. And now we are where we wanted to be, for the above has at least made it acceptable that there is a general relation between the curved path of a ray of light under the influence of gravitation and the theory of relativity.

The Straight Line in Space—(*continued*)

Let us return to our rays of light which, emitted by the stars, reach the Earth after passing close to the sun's edge. How shall we be able to demonstrate the apparent displacement, as if they were repelled by the sun? In principle it seems very simple. We make a photograph of some part of the zodiac at night, therefore at a time of the year when the sun is on the other side of the zodiac. Half a year later the sun is in the photographed part of the zodiac, and now we make another photo, compare the two pictures and accurately measure out the places of the stars close to the sun!

If Einstein is right, the second photo must show the Einstein effect, that is the stars must have been subject to apparent displacements away from the sun's edge.

This seems very simple in theory, but in reality the method is impracticable. True, it *is* possible to photograph stars, at least bright ones, in the day-time through a powerful

telescope, but in the immediate vicinity of the sun this is out of the question. The sunlight would then blacken the whole plate in the time of exposure wanted for getting the stars on the plate.

So here only one occurrence can give us our chance, a total solar eclipse. It is then possible, during the few minutes of totality, to make a photo of the immediate surroundings of the sun and to fix the places of the stars. Einstein himself pointed out the possibility of checking his theory in this way. This opportunity might not be allowed to pass, for it was the only possibility Einstein saw beside the shift in the solar spectrum, which, however, is difficult to verify. (*See* what we said on page 197 on the shift of the perihelion of Mercury, and on page 284 about the Companion of Sirius.)

No wonder that the next total solar eclipse was eagerly looked forward to by astronomers and the whole scientific world. All necessary preparations were made; quite a number of astronomical expeditions, equipped with the best instruments, set out to test Einstein's theory. Photos were taken and compared with pictures of the same part of the heavens taken several months previously. For months on end the places of the various stars visible on the photos were determined with the greatest precision attainable. It was here a question of fractions of seconds of arc! And—Einstein emerged triumphant. Not only was it proved that the Einstein effect was in evidence beyond any doubt, but the measure of displacement of the different stars tallied, within the errors of observation, with what Einstein had predicted.[1] It will be understood that this displacement was greatest near the edge of the sun, and decreased farther away from it. In this way it was proved that a ray of light was curved under the influence of gravitation. A revolutionary fact indeed! For, as the gravitational effect is omnipresent in

[1] It seems that the very latest measurings, made during subsequent solar eclipses, have shown that the displacement is slightly *larger* than that calculated by Einstein. If this should be confirmed there will be a new problem awaiting solution.

the Universe, so that there is everywhere a certain field of gravity, *a ray of light will invariably describe a curved path,* although we can only prove this statement in the case of a very strong field of gravity like that in the immediate vicinity of the sun. Any ray of light, straight in space, is bent because space itself is bent in consequence of the matter it contains, or rather encloses.

But here the reader will presumably refuse to follow me. Curved space? That is unacceptable by the ordinary man. But there are many things which ordinary people have refused to believe at first sight.

We invariably return to the same example: the curvature of the Earth's surface. A straight line remains a straight line on the surface of the Earth, even though such a line, owing to the curvature of the Earth's surface, will bend back on itself.

In like manner a ray of light remains a straight line in space, although owing to the curvature of space it also bends back on itself.

You refuse to accept the idea of curved space, you cannot conceive such a thing, whereas a curved surface is quite intelligible to you? But why then, dear reader, cannot you conceive a curved space? Are you quite sure you are able to imagine a straight space?

A Voyage round the World

Let us try, by a somewhat bold image, to shed some more light on how this bears on the problem as to whether the Universe is finite or infinite. Looking at the nocturnal sky in London I see a star in the heavens. I want to travel in that direction in space. I take a jump and lo, the next instant I land on the star. In thought I can travel very much faster than light. Sitting on my star I perceive our sun as a tiny star in the sky. I carefully note the direction, the straight line along which I travelled. I want to continue my journey through space in the same direction, and so I

carefully search for a star that lies in a direction exactly opposite to the one from which I arrived. I see one—a jump, there we are. I again carefully note the direction from which I arrived and look for a star exactly in the opposite direction, and so I travel on in a perfectly straight line, continually checking my path by means of rays of light, jumping from one star to another. Always in the same direction, in the same way as light is propagated through space. This goes on for years, centuries, hundreds, thousands of ages.

Again I see a star right in my direction. I make ready to jump, but at the last moment a dark, heavenly body, which is close to the star picked out by me, pushes past it and obstructs my path. So instead of reaching my star I land on the dark body and, just fancy, where should I be but on my good old Earth, in Trafalgar Square in London! So here I am back in my home, I, who thought I had left sun, Earth, London, behind for good and all! Yet my astonishment was of the same kind as that of the man who, by travelling in the same direction on the Earth's surface, finally reached his point of departure. I, too, have come back to my starting-point, after completing my journey round the world, round the Universe, after travelling through space in a perfectly straight line and—having unconsciously changed my direction with the curvature of space.

Like the Earth's surface the Universe is unbounded but not infinite. Moving in a straight line in the same direction we return to our point of issue. Here lies the solution of the seemingly insoluble problem discussed on page 320.

This is the great, new truth revealed by Einstein.

Naturally, there remain questions, numerous questions and difficulties for everybody. Difficulties about which only prolonged thinking can set our minds at rest. I am satisfied if I have succeeded in giving the reader a first glimpse of fresh possibilities.

Dimensions of the Universe

What, then, is the size of the Universe, what are its dimensions? It must be possible to find these, if the Universe is not infinite. What is the *radius* of the Universe?

The radius of the Universe? Who would have ventured to speak of such a thing five-and-twenty years ago? Now this radius is one of the topics of astronomy.

Some ten years ago there were two main conceptions as to the size of this radius: Einstein's and De Sitter's Universe. The difference between the theories of Einstein and De Sitter was settled in a way as simple as it was radical: both theories proved to be untenable.

The honour of having found the solution to this puzzle is due to Father Lemaître,[1] a Belgian scientist. The radius of the Universe is not a fixed, immutable magnitude. The Universe is *expanding*. This is the famous theory of the expanding Universe that has in a short time become common property of the scientific world.

The now almost universally accepted conception of the size of the Universe is as follows:

Some milliards of years ago the radius of the Universe was about a milliard light-years. At present this radius has reached two to twenty times that size. The expansion is now taking place at such a rate that in about 1,400 million years the radius will again be doubled. The layman is sometimes under the impression that astronomers make more positive assertions than they can answer for. But the above may be a proof to the contrary. Here an uncertainty ten times amplified is admitted in regard to the present radius of the Universe. This uncertainty, however, need not be lasting. Eddington has already indicated ways and means of finding a solution to the problem.

The Quantity of Matter in the Universe

In regard to the quantity of matter in the Universe,

[1] It afterwards appeared that the same thought had been expressed by Friedmann.

astronomers do not hesitate to give positive figures. The number of protons and electrons (these form the building materials of the atom) in the Universe is generally estimated to be of the order of magnitude of 10^{79}, that means, a 1 followed by 79 noughts. The weight of all matter in the Universe is of the order of 10^{55} grammes, that is, 1 followed by 55 noughts. This quantity of matter would be sufficient to form a number of heavenly bodies of the mass of our sun equal to 10^{22} or 1 followed by 22 noughts, that is *ten thousand trillion*. If now you would like to know how many stars the Universe contains, you should remember that part of this material is in the form of cosmic matter and, further, that a very great but unknown part of it has not yet crystallized into stars. Hence for the time being no more accurate answer to this question can be given than that the number is certainly many tens of trillions.

In connection with the uncertainty as to the present radius of the Universe it is impossible to give a positive opinion on the density of matter in the Universe. The astronomer Hubble estimates the density at the order of magnitude of 10^{-31} times that of water. This means $\frac{1}{10^{31}}$ times the density of water, that is, 1 divided by 1 with 31 noughts $\frac{1}{10000000000000000000000000000000}$. Jeans compares this to the density of a swarm of bees: 3 bees over Europe!

The Expanding Universe

We must now say a few words on this remarkable expansion of the Universe. Lemaître has shown that from the theory of relativity it follows that the radius of the Universe cannot be invariable, and that the expansion, once started, will progress at an ever-increasing pace. Eddington even professes to calculate from the structure of the atom, more particularly from the mass-relation of proton to electron, the rate of expansion of the Universe!

So far the theory. And now for actual observation. This indeed shows (Doppler effect, *see* page 291) that the stellar systems are rushing away from us at great speed,

the faster as they are remoter. Their velocities prove to be proportional to their distances, exactly what the theory of an expanding Universe demands. There are several reasons which, for the present, make it impossible to determine these velocities with perfect accuracy. But for the remotest stellar systems it is several thousands of miles per second. These are the greatest velocities that have so far been found to exist in the Universe (barring, of course, the velocity of light). We saw that the velocity increases in proportion to the distance; it may be said that the velocity, by the usual scale of distances of nebulæ, increases by 300 to 600 miles per second, per *megaparsec*. This is a new measure of distance. The light-year and the light-century are far too small here. A parsec is the distance at which the parallax is one second of arc, hence about 3¼ light-years. One megaparsec is one million parsec, hence about 3¼ million light-years. The remotest stellar systems are about 40 megaparsec away from us (by the usual scale of distances). So they must recede from us with a speed of about 40 × (300 to 600) miles per second. And their velocities indeed prove to be of that order of magnitude.[1]

But do not you think it strange that all stellar systems should run away from *us*? Do they shun our company, our Galactic system? No, that is not how it is. *All stellar systems run away from one another!* Their own dimensions, however, are stationary. This can best be made clear by the following example: Imagine 25 people sitting in a large hall in 5 rows of 5. The rows are now removed from one another to twice the original distance, while in each row the same is done with the chairs. This done, everybody is at twice the distance from his neighbour that he was at first. This is an example in two dimensions, but it is easy to imagine it in three dimensions. Everybody who was at

[1] If it is true that the stellar systems are at considerably greater distances than was generally accepted hitherto (*see* previous chapter), the above-mentioned increase in speed (300 to 600 miles per second per megaparsec) will turn out to be quite appreciably smaller. But the speed of the nebulæ is not changed on that account. For their distance is then correspondingly greater.

2 yards' distance from another person is then 4 yards away from him. A man who was 10 yards away is now at a distance of 20 yards. So in our example, too, the measure of removal is proportional to the distance.

The Universe expands, with increasing speed, but these newly discovered facts are far from being rounded off on all sides. And how could they be? It is barely five years ago that this new revolutionary truth was discovered! Especially the remote past and the distant future are—as always—mysteries. Will the expansion progress with ever-increasing speed? Until the greatest possible velocity, that of light, has been reached? The investigations of the coming years and decades will have to supply the answer. And as to the past: what was the situation before the beginning of expansion some milliards of years ago? The greatest difficulty is not here the length, but the amazing shortness of this period. If the theory told us that the expansion had been going on for tens of billions of years, there would be no difficulty. Then development and expansion of the Universe would coincide. For—we will revert to it in the last chapter—the evolution of the stellar systems and of the stars must be measured by billions and tens of billions of years. A few milliards are as a day.

As we shall presently see, some milliards of years have sufficed for the formation of our solar system. But a stellar system cannot have attained its present stage of development in the time sufficient for a paltry solar system. De Sitter rightly says that very few astronomers would be content with a time-scale of some milliards of years for the construction of stellar systems and the evolution of stars. A great many astronomical facts go to make it unacceptable. The most important is the relation between the mass and luminosity of a star as discovered by Eddington (*see* page 279). A great mass means great luminosity; a small mass, small luminosity. As yet there is still much that is unknown in the evolution of the stars, but Eddington's law makes it highly probable that stars develop from bodies of great mass

and great luminosity to bodies of small mass and small luminosity. The stars radiate and are thereby subject to continual loss of mass: mass is converted into radiation. From the luminosity follows the quantity of matter that is converted into radiation during a given unit of time and from the total loss in mass suffered by an "old" star in comparison with a "young" star, the age of the star can be deduced. In this way we find an age, a time-scale, of *billions* of years.

But even a plain-minded man, like the present writer, cannot believe that the stellar systems should be of about the same age as the oldest rocks on Earth! To my mind geological and cosmological eras are so wide apart in order of magnitude that it seems as incongruous to draw a parallel between them as between historical and geological eras.

So the beginning of the expansion of the Universe cannot at the same time have been the beginning of its evolution. Nor need this be so. De Sitter compares the moment when expansion commenced, hence the moment of the smallest distances, to the passing of a planet or comet through its perihelion. Before that there may therefore have been "contraction" instead of "expansion," and this possibility also follows from the latest theoretical studies of Einstein and De Sitter.

We shall now give a brief summary of our knowledge —as yet incomplete and preliminary—of the Universe.

The Universe is unbounded but not infinite. It practically consists of . . . nothing at all; it is of an alarming emptiness: "three bees above Europe." In a space with a radius of some milliards of light-years (1 light-year=6 billion miles) there are milliards of stellar systems each containing sufficient material for several tens of milliards of stars. A great part of the material is still shapeless. One of these milliards of stellar systems is our Milky Way. The Universe is expanding with increasing speed.

Our sun is one of the 100 to 200 milliard stars of the Milky Way. It makes one revolution with the wheel of the Milky Way in about 200 million years. The sun is the centre of our solar system. Nine small globes, the planets, revolve about the sun. The third of these planets, from the sun, is our Earth, less than one-millionth part of the sun in size. On this Earth lives man!

This is the home we inhabit. How far behind us lies the time when the Earth was believed to be the centre of the Universe.

How inconceivably greater than was then surmised is the Creation to him who believes in a Creator! And he who cannot believe in a Creator, should not he, too, bow his head before this wonderful and mysterious Universe?

CHAPTER XII

PAST AND FUTURE

ONCE, in the very beginning of time, there was a rarefied, unshaped, primary nebula that filled the whole Universe with equal density everywhere. Where, when and how did this nebula originate? One can think of it as being created by the Creator, as a materialization of the spirit of the world, or as the undefinable great mystery. Let each man hold his own innermost conviction. It is only the fool who thinks there is no mystery at all in it; to whom everything, without wonders, just "happened."

Origin of the Stellar Systems and the Stars

In that vast primary nebula everything did not perpetually remain in undisturbed equilibrium. There were local condensations and this caused further concentration. This is where astronomical science begins. Science can prove mathematically that from the primary nebula separate nebulæ must have been formed in this manner separate balls of gaseous matter, from which the stellar systems were to be born. It can even prove that the mass of these separate balls of gaseous matter must be of the same order of magnitude as that of the present stellar systems.

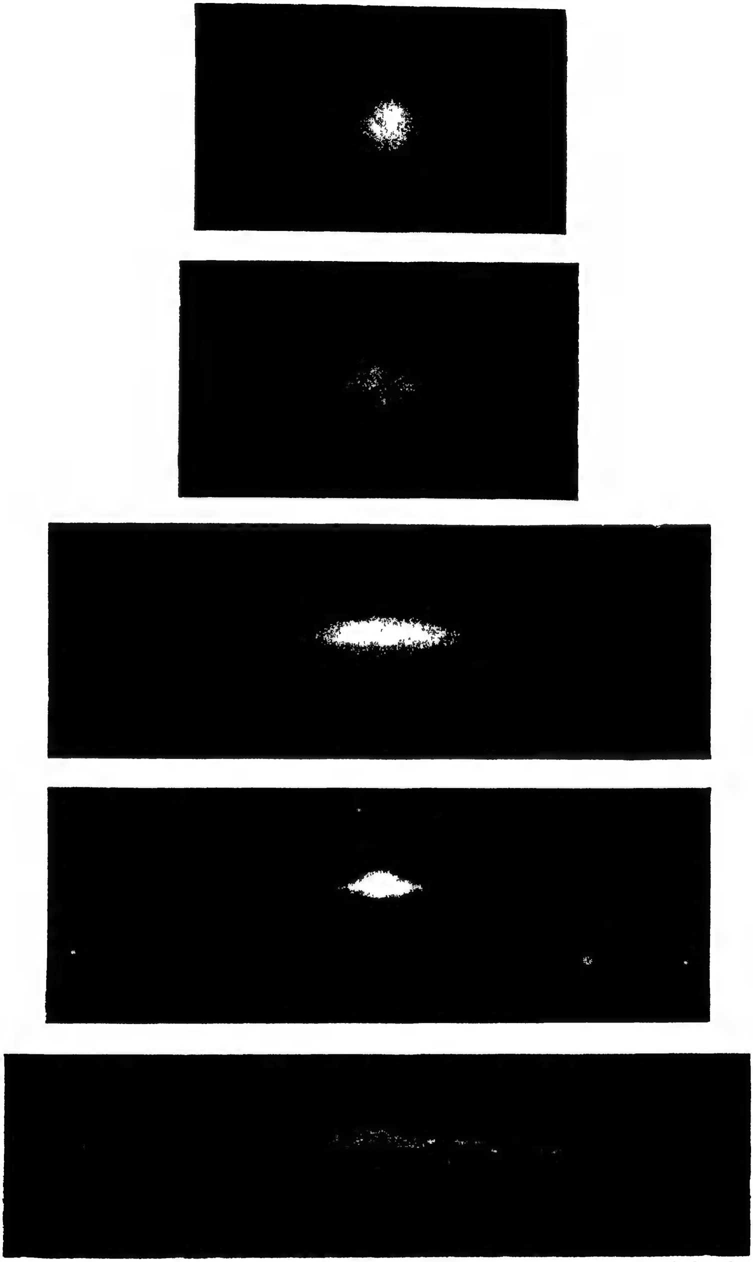
The primary nebula dissolves into milliards of separate balls of gas. This is where the second act of the world drama begins. The evolution of the separate stellar systems commences. Some of these systems will remain as they are, practically unchanged, for billions of years. Others, after varying periods of time, will gradually start to rotate. They will slowly be flattened out by this rotation and gradually

become more and more disk-like or spiral-shaped. Their greatest diameter increases during this process. And again it can be mathematically shown that this rotating mass of glowing gas cannot remain in this condition, but local concentrations must again be formed, this time on a much smaller scale. *The first stars are born.* And again mathematics can prove what magnitude the mass of a thus crystallized star must be! It must be of the order of magnitude of the present stars. It is with justifiable pride that Eddington states that mankind would be able to calculate the mass of a star without ever having seen one. It is with an overwhelming, almost oppressive sense of its beauty that even at the present day we see this evolution happening before our own eyes. Of course not in one same stellar system. Our lives and the life of mankind on Earth so far are too brief for that. We already discussed the different shapes of these systems (page 310). No one, seeing the photographs, need be in any doubt as to the order in which they should be arranged to illustrate this process. First the ball-shaped form, then the flattening, then the rotating disks and spirals in which the stars are seen to be born, first on the edge, later in the middle too, and finally the complete stellar systems almost entirely dissolved into stars!

We see here before us the nebular hypothesis of Kant-Laplace on an infinitely magnified scale. Kant and Laplace both believed that from the rotating nebulæ solar systems were born, that this is how the planets were formed. They were mistaken, but their doctrine is restored to honour a milliardfold: from the nebulæ *stellar* systems are born; *stars* are originated there. The time that elapses before the birth of stars may be estimated at an order of magnitude of some tens of billions of years. The star itself also has a lifetime of some tens of billions of years allotted to it.

How is it, you will ask, that astronomers are able to assure us of this with such certainty? Some words were already given to this matter (page 166). We owe it to astrophysics,

that new branch of science to which we have several times referred before. The new theories about the structure of the atom help us to understand the evolution of the stars. It is admirable how much has been accomplished in this field in the course of a very few years: in Eddington's book *Stars and Atoms* it is excellently dealt with. It has been realized that in the stars, part, if not the greater part, of the energy in the interior of the atom is released; matter is continually converted into energy, into radiation. The reader will probably at one time or another have heard of the incredible amount of latent energy in an atom. If we were able to release this energy, one or two cubic inches of coal would be enough to take a steamer to the other side of the ocean. The energy that we arouse by our process of combustion, compared to intra-atomic energy, is what the breathing of a baby is compared to a raging hurricane. It was formerly held that the stars derived all their heat from contraction from a gaseous nebula of much greater dimensions; people were not aware of intra-atomic energy in those days. The amount of radiation of the stars, and of the sun in particular, could be calculated with great exactitude; and also the loss of stored energy that must ensue annually. And thus it could be computed how long the source of energy originating in this contraction would last to provide sufficient energy for this radiation. It was by this means found that the sun could last but some tens of millions of years. But it is now known that an infinitely vaster store of energy is there, and the well will continue to yield not for millions, but for billions of years to come! And more and more has become known about the life of a star from youth to age; gradually we are getting to know the various stages of its life and the duration of these periods, and from its condition, from the light it sends us, notably from its spectrum, we may derive its age. There is a whole series of stages, and corresponding spectra, through which a star has to pass. This might easily be explained in popular terms, but we should then have to explain the structure of an atom, to deal with electrons, protons, the



Different shapes of nebulæ. Looking at this from the top we see nebulæ in increasing states of development.

various radiations in the atom, and so on, and this would take us too far. That would not be a chapter, but a book in itself, on physics and chemistry. So the reader will have to be satisfied with the assurance that a star passes through a series of stages of development. With regard to the question as to how these stages succeed one another, astronomers are not quite agreed on this point—we must in all honesty add this. They do agree that ultimately, at the end of billions and billions of years, the inevitable moment comes that a star dies out, that most of its matter has been converted into energy. Then, very gradually, the star cools down and dies.

But we had not got to that part of the story yet. Our star has just been born. And again it is mathematics that teaches us that such a star must start to rotate, and that the velocity will increase, at least at first. When the rotation exceeds a certain limit, it is likely that the star will split up into two components: *a double star is formed.* But this rotating star—again mathematics comes to our aid to prove it—can never, without a "new fact," evolve into a solar system, such as ours is. This is why the Kant-Laplace theory, which can now be considered as proven with regard to the birth of the *stellar* systems, can never account for the origin of one single planetary system. Mathematical theory can prove that except for the possible splitting up into a double star, there can be no further development of the star without a "new fact."

From this it follows that a planetary system can certainly not be considered as a normal appendix to a star. In former times, in the line of thought of Kant and Laplace, the presence of a planetary system near every star was thought to be normal. People thought they were justified in calling the existence of milliards of planets, more numerous even than the stars, a matter of course. Every star was looked upon as the centre of a planetary system that practically could not but have developed from the primary nebula from which the star had originated by contraction.

But mathematics has now taught us to think differently. We know one planetary system with certainty—our own. The existence of planetary systems of at least some other stars remains highly probable; it would indeed be odd if, among trillions of suns, our sun should happen to be the only one having planets as children. It is extremely important in connection with the question as to whether there are other inhabited worlds or not. One thing is quite certain: unless our means of observation are immensely improved we shall never be able to observe other planetary systems; the distances are too great. Pluto is on the very border of visibility; the nearest stars are ten thousand times as far away! How could we possibly see their planets, whose light at that distance, even though it were a hundred times that of Pluto, would be a million times as faint here?

Although we cannot actually see other planetary systems —they might exist. To be able to form an opinion as to the likelihood of this we must try to get some idea of the origination of our planetary system. And apart from this, the question as to how our Earth came to be born is doubtless of the greatest interest. So we shall now have to give our attention to this problem.

Origin of the Solar System

Since the nebular hypothesis of Kant-Laplace was abandoned, no theory about the origin of the solar system has found more supporters than that which is known as the Tidal Theory, which was most fully developed by the English astronomer Sir James Jeans. Jeffreys also contributed an important share to its further formulation. Jeans is a fine astronomer, and perhaps the best propagandist of astronomical knowledge of our times, the Flammarion of this century. So let us ask him to tell us about this theory himself: listen how he describes the birth of our planetary system in his excellent book *The Stars in Their Courses* (page 44[1]). He takes us back two or three milliard years in time. This is

[1] Quoted by kind permission of the Cambridge University Press.

quite a short period in the life of the sun—what a few weeks are in a human being's lifetime.

"As we cruise about near the sun, and watch the changing panorama of the sky somewhere between two and three thousand million years ago, we notice a star gradually increasing in brightness until it outshines all the others in brilliancy, and finally looks incomparably brighter than Sirius does now. It looks bright because it is very near rather than because it is intrinsically very bright; indeed, it has approached quite unusually near to the sun. And as we watch, it comes ever nearer; it is heading almost straight for the sun. It is no longer a mere point of light. We see it as a large disk. And now it has come so near that its mechanical effects are beginning to show. Just as the moon, by its nearness to the Earth, raises tides in our oceans, so this enormously more massive body is, by its nearness, raising tides in the fiery atmosphere of the sun. Because it is so much more massive than the moon, these tides are incomparably greater than those which the moon raises in the earth. They become so great that, at a point right under the star, the sun's atmosphere is drawn up to form a huge mountain, many thousands of miles high. This mountain travels over the surface of the sun, keeping always under the star which causes it, as this moves on its way through space. At the opposite point of the sun's surface, another but smaller mountain keeps always opposite the main one. As the star approaches ever nearer, these tidal mountains continue to increase in height, until at last, when the other star is so near as to fill up a large part of the sky, a new feature enters. So far, the gravitational pull of the star has been drawing up the summit of the larger mountain in opposition to the gravitational pull of the sun, but the latter has always been the stronger. Now the second star comes so near that the balance suddenly swings over in the other direction; the second star outdoes the sun in gravitational pull, and the top of the mountain shoots off towards it. As this relieves the pressure on the lower parts of the mountain,

these also shoot upwards, and then the parts below them, and so on, so that a whole stream of matter shoots out from the sun towards the second star. If this star came continually near to the sun, the end of the jet of matter would reach it in time, and the substance of the jet would join the two stars together like the bar of a dumb-bell.

"Actually the other star is not heading directly towards the sun; after coming very near indeed, it finally passes on its way without actually colliding. As it recedes its tidal pull diminishes. No more matter is pulled off the sun, and the jet which has already come off forms a long filament of hot filmy gas suspended in space. In shape, it is rather like a cigar, pointed at its two ends. The point which is now farthest from the sun was originally the peak of the tidal mountain. The thick middle of the cigar consists of the matter which came off plentifully when the star was nearest, and its tidal pull was strongest. Finally the pointed end nearest the sun is formed of the last thin dribble of matter which came off just before the tidal pull became too weak to draw any more matter away from the sun.

"Even as we watch this cigar-shaped filament of fiery spray, it gradually cools and, as it does so, it condenses into detached separate drops, much as a cloud of steam condenses into drops of water. Yet these drops, like the filament itself, are colossal structures; their size is on the astronomical scale. Naturally they are biggest near the fat centre of the cigar, where the matter of the filament was most abundant, and are smallest at the two ends.

"Finally, these detached drops of matter begin to move about in space as separate bodies. They do not fall back into the sun, because the pull of the other star, which we now see receding in the distance, has set them in motion; unless they happen to be moving directly towards the sun, they will not fall into it but describe orbits round it. This is a direct consequence of the law of gravitation, which was the same thousands of millions of years ago as it is to-day. Some of these orbits may be nearly circular while others are

greatly elongated. As we watch the orbits for millions upon millions of years, we see them gradually and very slowly changing their shapes. The condensed drops of matter do not move in unobstructed paths, for the great cataclysm we have just witnessed has left space littered with its debris. The great drops must plough their way through this, and as they do so the shapes of their orbits gradually change, until at last, after thousands of millions of years, they move round the sun in almost circular orbits, just like the planets of to-day. And indeed these bodies are the planets; the dramatic spectacle we have just witnessed from our imaginary rocket is one which must inevitably happen in Nature whenever one star approaches close enough to another, and its final scene is so exactly like the solar system, that we have every reason to suppose that this is actually the way in which the planets came into being. So far as we can judge from their present arrangement and movements, it seems most likely that they were torn off the surface of the sun by the tidal pull of a passing star which happened to pass very unusually near to it some few thousands of millions of years ago."

We have already said that no theory about the origin of the planetary system has found more supporters than this one. We may perhaps be even more sweeping still and say that it is fairly generally accepted nowadays. It owes this to its great merits, to its great explanatory force.

Before we proceed to discuss this more in detail, we should first like to explain why it is that Jeans places the time of the birth of our planetary system—and hence also of our Earth—as far back as two to three milliard years ago. Although there may still be some difference of opinion about Jeans's theory, there can be none on the age of the planetary system and the Earth. There are few periods in the history of the world and of the human race of whose duration we are as sure as we are about this. There are numbers of facts of the most diverse kind to prove it: astronomical facts about the various parts of our solar system; geological facts

concerning the age of the oldest stones of our Earth, derived from various data; and of recent times investigations into the age of meteorites (*see* page 237). And they all invariably point to the same age of two to three milliard years. And again we must insist that in the history of the evolution of the world this is but as yesterday.

We now come to the facts that enhance the probability of Jeans's theory. In the first place, the magnitude of the various planets. Starting from the sun, we first come to the small planet Mercury; then to the next, Venus, a little larger; then the Earth, about the same size as Venus; then Mars, which is smaller and does not seem to fit properly into this series; next Jupiter and Saturn, the giants of our solar system; then Uranus and Neptune, considerably smaller again; and finally the small planet, Pluto, which is probably very small indeed. With the exception of Mars, they all fit wondrously well into the cigar shape which, according to Jeans, the part of the solar matter ejected by the sun must have possessed. *Must* have possessed because first the tidal force was weak, then at the approach of our parent star it got stronger and stronger, to decline again as it passed away. Jeans's theory had been fully formulated before the discovery of Pluto: the fact that this was so small was again a point in favour of the theory. This is why we said on page 222 that, should there exist any unknown planets farther away, these would prove to be small, probably even very small.

Then follows the proof on the strength of the position and shape of the orbits. It was always a very weak spot in the nebular hypothesis of Kant and Laplace that the mean orbital plane of the planets (generally, the reader will remember, these planes are at but very slight angles to each other) does not coincide with the rotational plane of the sun, but is at no inconsiderable angle to it (about seven degrees). According to the nebular hypothesis, without the aid of other ancillary hypotheses, these planes should have coincided. But the tidal theory demands this deviation, it

would be a vulnerable spot in its argumentation if this deviation did not exist. For here we see the influence of the orbital plane of the paternal sun, which left its last trace in this angle of inclination; a trace that is unfortunately too weak to be an aid in affiliation of our solar system on one of the stars.

Another proof is afforded by the eccentricity of the orbits, about which Jeans made a few observations in the above quotation. The orbits of the innermost and outermost planets Mercury and Pluto are the most eccentric, which, according to the tidal theory, is exactly what one must expect for the outermost planets, where least interplanetary "grit" must have been formed. Furthermore, the planets usually have less eccentric orbits as they are larger—the larger the planet the more friction there is against the "grit," the greater the loss of eccentricity.

The Birth of the Satellites

Finally, there are the satellites of the planets, and their nature in general; their size and distribution bear out the tidal theory very well.

It must first be remarked that there is great similarity between the systems of planets with their moons and that of the sun with the planets. The size relation of the mother planet to her moon children is of the same order of magnitude as that of the mother sun to her planet children. There is only one exception, and that is the Earth to the moon, our moon being too large. If planets, as for instance Saturn and Jupiter, have many satellites, then generally the middle ones are largest, the outermost and innermost smallest, just as the planets of the solar system. So we see that it is correct to say that the satellite systems are in many respects miniature planetary systems. This would seem to indicate that there must have been some similitude between the causes that led to the formation of the planetary system and that of the satellite systems.

Now we saw that originally the orbits of the planets

were greatly elongated—in part of their orbits they must then have approached very close to the sun. The sun could thus give rise to tides of tremendous force on the planets. The planets had then, in all probability, not yet sufficiently cooled down to have solidified. The larger ones, Jupiter and Saturn, were no doubt still in a gaseous state, the smaller ones probably became liquid comparatively rapidly. Both on the gaseous and on the liquid planets the tidal force of the sun could cause the formation of a tidal cigar. Now one feels by intuition that this happens more easily with gaseous bodies than with liquid ones, and it also seems obvious that if a "cigar" is actually ejected from a liquid planet a larger quantity of the liquid planet will be taken from it. Mathematical theory confirms both these facts. So, according to the tidal theory, we might expect that the large planets, which longest remained in a gaseous state, should have a large number of comparatively small satellites, then should follow smaller planets with a small number of comparatively large satellites, and finally smaller planets still without satellites. This is indeed how it is in the solar system: Jupiter and Saturn have a large number of comparatively small satellites, Mars has two small satellites, the Earth one large moon, while Venus and Mercury have none at all. And now, looking the other way: Uranus has, comparatively speaking, many small satellites, Neptune one comparatively large moon. The only planet that does not really fit into our scheme is again Mars. Considering its place in the solar system it ought to be larger than it is, and as regards its satellites it has the retinue of a larger planet. So here are two indications that Mars must originally have been larger than it is now!

The age of our moon can be fixed at about two milliard years on the strength of a number of astronomical data. This age also goes to prove the fact that it must have been born of Mother Earth, not long after the Earth itself came into existence.

So we see that theory tallies most remarkably well with

fact. If everything corresponded down to the smallest detail . . . it would be too good to be true!

As far as our present knowledge goes we may therefore regard the tidal theory as a successful attempt to give an explanation of the origin and structure of our solar system.

The Element of Chance

Yet, at first sight, there would appear to be a serious objection to one part of this theory.

The encounter between the parent suns would appear to be a coincidence. Now science justly does not put much belief in a coincidence; really, science and coincidence are diametrically opposed. And this particular coincidence is a very special one, a most exceptional coincidence! It is possible to calculate to within certain limits of accuracy the chance that two stars in our Universe approach one another close enough to cause the birth of a planetary system. This chance proves to be extremely slight: remember the three bees over Europe. Therefore the number of suns with planets round them ought to be extremely small in proportion, too. So this would mean that our sun belongs to the chosen few. One sun with planets to milliards of suns without. And of an origin so wild, so crude, so inharmonious, so unbefitting in a cosmos, which word surely does not for nothing mean "order."

The Expanding Universe and the Tidal Theory

Although a few arguments, borrowed from the familiar profusion of nature, could be placed over against it, the objection remained serious. The theory of the expanding Universe, however, unintentionally offers a way out of the difficulty. According to that theory the Universe must have reached its minimum dimensions some milliards of years ago: its radius was then very much smaller than it is now—the various stellar systems must have been crowded very close together. According to De Sitter it follows from

mathematical theory that the stellar systems had approached very close together during a short period, and interpenetrated at great velocities. This was some milliards of years ago, the same time at which the solar system came into existence. *Now the coincidence is no longer a coincidence.* Now one would almost be tempted to make biological comparisons between stellar systems impregnating each other. We shall not deviate down this fantastic path, but no one can deny that this new insight materially strengthens the tidal theory. The odds in favour of two stars approaching close to one another were then in any case very much greater than they are at the present stage of evolution of the Universe.

The close approach of the stellar systems to each other has in all likelihood left yet another trace. For we have seen that the density with which the stars are scattered in our own Milky Way and also in many nebulæ varies greatly at different points. Now mathematical theory says that such unequal density in a rotating disk cannot continue, but is bound to be eliminated after a small number of rotations. About ten rotations can probably in this respect be regarded as a small number. One rotation is of the order of a few hundred million years. Our Milky Way and the other stellar systems can therefore have been in the present state of unequal density for at most a few milliard years—otherwise the last trace of this inequality would already have been obliterated. Well then, here again the cumulation and partial interpenetration of the stellar systems, some milliards of years ago, affords an unexpected clue to the cause of the unequal densities and the fact that they are still in evidence.

Are there any other Planetary Systems?

Let us return to the origin of the planetary systems. Thanks to the penetration theory we may assume that planetary systems are not so rare after all. Theory at present does not permit us to estimate their number, and perhaps will never provide a clue. But even if that chance

were only one to a million, among the trillions of stars in existence there must be billions with planetary systems.

Are there other Inhabited Worlds?

The question as to whether these planetary systems exist or not is of the greatest importance in helping us to decide whether there are any other inhabited worlds, or, more generally, other worlds in the Universe on which living beings occur. In giving a reply to this question we must in the first place observe that any kind of life, as we understand it, is impossible on the stars. One cannot, with any semblance of reason, speak of the possibility of life on the sun or on the stars, on whose surface (let alone in their interior) temperatures of many thousands or tens of thousands of degrees prevail. It is true, one must be cautious in denying the possibility of life. Life has an almost limitless faculty for adaptation. Before the fishes were known that occur in the lowest depths of the ocean, we were told exactly why no life was possible at such depths. Was not the pressure much too high, and was it not because the sunlight could not possibly penetrate so far into the sea? When the time came, however, that nets were constructed with which the oceans were swept at immense depths, numberless fishes were found happily living and thriving there. They proved to be perfectly adapted to the high pressures and to carry their own "electric" light, while their eyes had often evolved to enormous sizes so as to be able to catch very faint light impressions. So we see that we must take good care not to underrate the adaptive capacity of life. But one must not go to the other extreme either. If anyone should maintain that life on the stars and on the sun is possible in a totally different form, this cannot be absolutely denied, certainly, but in reality it can only be admitted for the sake of argument! If life were something totally different from what it is, it would also be conceivable and possible under totally different conditions. But, put that way, our problem becomes quite void of sense.

So, in our search for life, we must stick to the planets and—perhaps—some of their satellites. Now we find that *the chance that there is any kind of life comparable to life on Earth in the planets of our solar system is very meagre.* Mercury is even worse off than our moon; and it is bad enough there in all conscience, as we saw in Chapter IV. Mercury always turns the same side to the sun, to which it is so close. On that side, as has been found by direct temperature determinations, it is hotter than hot; on the other side, where the sun never shines, it is colder than cold: not much above the absolute zero ($-273°$ C.). There is no oxygen, not a drop of water. No life can possibly exist on Mercury.

The outer planets: Pluto, Neptune, Uranus? We know next to nothing with any certainty about conditions on these planets. One thing is sure: the heat that reaches them from the sun must be very slight. It is not likely that there is our kind of life there. Jupiter and Saturn? Here again we cannot say much with certainty. But the general impression we get is not in favour of life. Jupiter's large satellites are very probably bodies like our moon.

That leaves us Venus and Mars. And, indeed, here we must be most careful. Very little is as yet known of Venus; even the question as to how it rotates—which is of the utmost importance for the possibility of life—has not yet been given a positively certain answer. Recent experiment has made it very likely again that the white clouds that permanently hide its true surface from us are indeed real clouds, consisting of particles of water. That means that it has water and an atmosphere dense enough to keep them drifting. This enhances the possibility for Venus. But uncertainty remains.

As far as we know, the best conditions for life are on Mars. Read again what was told about it in Chapter VII. It has become extremely likely that there is vegetation on Mars. And vegetable life can naturally make animal life possible. To the question as to whether there are beings endowed

with reason on Mars, we can give no answer. To us humans, life would not be possible there without expensive, artificial aids. All the rest is more or less speculation. With a fair degree of probability it may be maintained that conditions must have been more favourable in former times on Mars. The planet is at a farther stage of its evolution than our Earth is. It is older, more lived out. Probably the "climate" used to be better at one time.

It is best not to speak of the life of "people" on other planets. There may be creatures endowed with reason. But that they should in any way resemble human beings does not follow of necessity, it is even improbable. If there is life, that life will have developed differently, as befits different conditions.

As regards the other unknown planets revolving round other suns, whose existence we may suspect in our Galactic system—it is best to say nothing at all about them. All we know about them is that there is a great chance that on some, or at least one, of them there are conditions strongly resembling those of our Earth. After all, there are so many!

We shall leave planets in other stellar systems out of consideration altogether.

The Origin of Life

Even if there should exist conditions favourable to life on a number of planets—which is extremely probable—yet, even then it is an open question whether there actually is life there. We are absolutely ignorant as regards the origin of life on Earth, and of the nature of this origination. What we do know with a fair degree of accuracy, is the condition of the Earth when, at least 300 million years ago, the first kind of life came into existence. We also know that life, gradually, in the course of tens and hundreds of millions of years, continually evolved to higher and higher forms. We know that at last the vertebrates and finally the mammals were formed and that, at least 300,000 years

ago, the first human-like creatures evolved from their ape-like ancestors. If any one thing was ever scientifically proved a thousand times over, it is the fact of evolution, the development of all that lives on Earth from one, or a few, simple basic forms. We cannot deal here with the fundamental causes of that evolution; there can be serious philosophical differences of opinion on that point. But the actual fact of evolution cannot be denied on scientific grounds. Neither can the origin of man from anthropoid beings be disproved after the finds of recent years, after what has become known about the Neanderthal man, about the Pithecanthropos, and about the Peking man.

Here too it is impossible to explain the commencement. Let there be one living cell and the whole vegetable and animal kingdom can grow from it. But no one in the world can say how the first living cell came into being, though we can understand why the chemical substances of which the living cell is built up did not occur until that moment on Earth.

Does life happen when and as soon as conditions are present that make life possible? Or must there be some more definite fact, perhaps some mere coincidence? A coincidence that occurred once on Earth, never to be repeated? Are there, perhaps, thousands, perhaps millions and tens of millions (counting the other stellar systems too) of planets in the Universe, where life would exist if only this same coincidence occurred?

Here again we touch upon matters of philosophy. Let every reader answer these questions according to his own religious or philosophical convictions. I, for my part, cannot believe that in the immeasurable Universe with its trillions of suns, only one small planet of one single sun should be inhabited. I feel bound to believe that there is also life on millions of other worlds, because otherwise to me the Universe would be entirely incomprehensible. I admit that Nature is profuse, in some ways even wastefully lavish: plants and trees distribute milliards of seeds, of

which only a few ever grow into new plants; but I cannot and do not wish to accept the idea that a Universe with trillions of suns should form the surroundings to one Earth with life and beings endowed with reason. I believe in the existence of millions of worlds with life on them, partly with life in a much more advanced stage of development, because the contrary would to my mind be an absurdity. I cannot admit that it is just chance that brings life to those worlds that have grown ripe to receive it. I wish to believe that the world is rational and beautiful, or that it will at least become so. And I believe that everywhere it is possible that the spirit of the Universe will reveal itself in rational beings.

Past and Future

The human race is still in its infancy. Mankind on Earth has a life of at least 300,000 years, at most a million years, behind it. Even if we assume the highest estimate to be right, it is still in its tenderest infancy. There is every reason to believe that our sun will continue to make life possible on Earth for billions of years more, more or less on the same scale as it exists now. Let us for a moment assume a very short estimate, say, one billion years. Even at this most meagre estimate, mankind has lived but one millionth part of its life as yet. As compared with the life of a human being, that is not quite three-quarters of an hour. Mankind is a baby, come into the world 40 minutes ago. The baby has still five and seventy years to go.

For a billion, perhaps several billions of years, mankind will be able to continue developing on Earth. Unthought of, undreamed of possibilities lie ahead. A wonderful future would seem to be in store for the human race. . . .

Until these billions of years also belong to the past, a second in eternity. Then the sun will die down, and with it life on Earth. A removal to another planet belonging to another sun, is not possible: this life is

bound to this Earth and this Mother Sun, and will die with her.

And again we hear: Whence? Whither? Why? Wherefore? We do not know, and never will know.

But in our hearts we can cherish the reassuring certainty that the Universal cannot but be good and beautiful.

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